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Conceptual Design Of A Space-Based Multimegawatt MHD Power System

Task 1 Topical Report
Volume II: Requirements Document

Prepared For

DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER
PITTSBURGH, PA 15236-0940

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JANUARY 1988

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LIST OF ACRONYMS

ACES	Action Commitment Expediting System
AESD	Advanced Energy Systems Division
APT	Advanced Power Train
ß	Hall parameter
BAC	Boeing Aerospace Company
CD	Control Drum
CDIF	Component Development and Integration Facility
C.G.	Center of Gravity
CMS	
CSS	Core Structural Support System
DOD	United States Department of Defense
DOE	United States Department of Energy
EMI	Electromagnetic Interference
EML	Electromagnetic Launchers
EMP	
ET	External Tank
EUT	Eindhoven University of Technology
FEL	Free Electron Lasers
GD&M	General Design and Mission
HEL	High Energy Lasers
ICD	Interface Control Drawing
IMACS	Integrated Management and Control System
INEL	Idaho National Engineering Laboratory
IUS	Inertial Upper Stage
KSC	
LANL	Los Alamos National Laboratory
MFCO	
MHD	Magnetohydrodynamic
MIP	
MIT	Massachusetts Institute of Technology
MMW	Multimegawatt
NDR	NERVA Derivative Reactor

LIST OF ACRONYMS (Continued)

NERVA	Nuclear Engine for Rocket Vehicle Application
NPB	Neutral Particle Beam
OMS	
OMV	Orbital Maneuvering Vehicle
P.C.	Power Conditioning
PCS	Power Conditioning System
PETC	Pittsburgh Energy Technology Center
PIP	
R&D	Research and Development
RCS	Reactor Control System
RMS	
RSS	Rotating Service Structure
RTLS	
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SPA	System Performance Analysis
STS	Space Transportation System
TBD	To Be Determined
TIT	Tokyo Institute of Technology
VRCS	Vernier Reactor Control System
WBS	Work Breakdown Structure

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1.0 INTRODUCTION

This report presents the system requirements and design guidelines for the space-based multimegawatt MHD power system conceptual design performed under Contract No. DE-AC22-87PC79665, and comprises Volume II of the topical report describing the Task 1 MHD Power System Conceptual Design and Development Plan.

The requirements and guidelines presented herein were used as the input to the Task 1 system parametric studies and the initial conceptual design. This report has been prepared as a separate volume to facilitate the updating of the requirement and guideline information as the effort proceeds through Task 2, Subsystem/Component Development, Analysis and Testing.

In the interest of completeness, this report includes a summary description of the MHD power system concept with the functional requirements, design scope and design objectives. Then subsequent sections present the system requirements including operational requirements, space platform/weapon system interfaces, subsystem interfaces, and design guidelines. The analytical methods used for system analysis and parametric studies are also included. A description of the MHD power system, in the standard data table format for multimegawatt space power systems, is included in the Appendices.

1.1 Power System Concept Description

The space-based multimegawatt MHD power system concept is illustrated schematically in Figure 1-1. The principal components are a gas-cooled, solid core nuclear reactor heat source and an MHD disc type generator.

The power system depicted in Figure 1-1 uses hydrogen as the working fluid and includes a dedicated liquid hydrogen supply subsystem. Candidate weapon systems currently under consideration require low temperature cooling during operation and cryogenic hydrogen is the most mass effective approach for this application. The hydrogen available from the weapon system can be

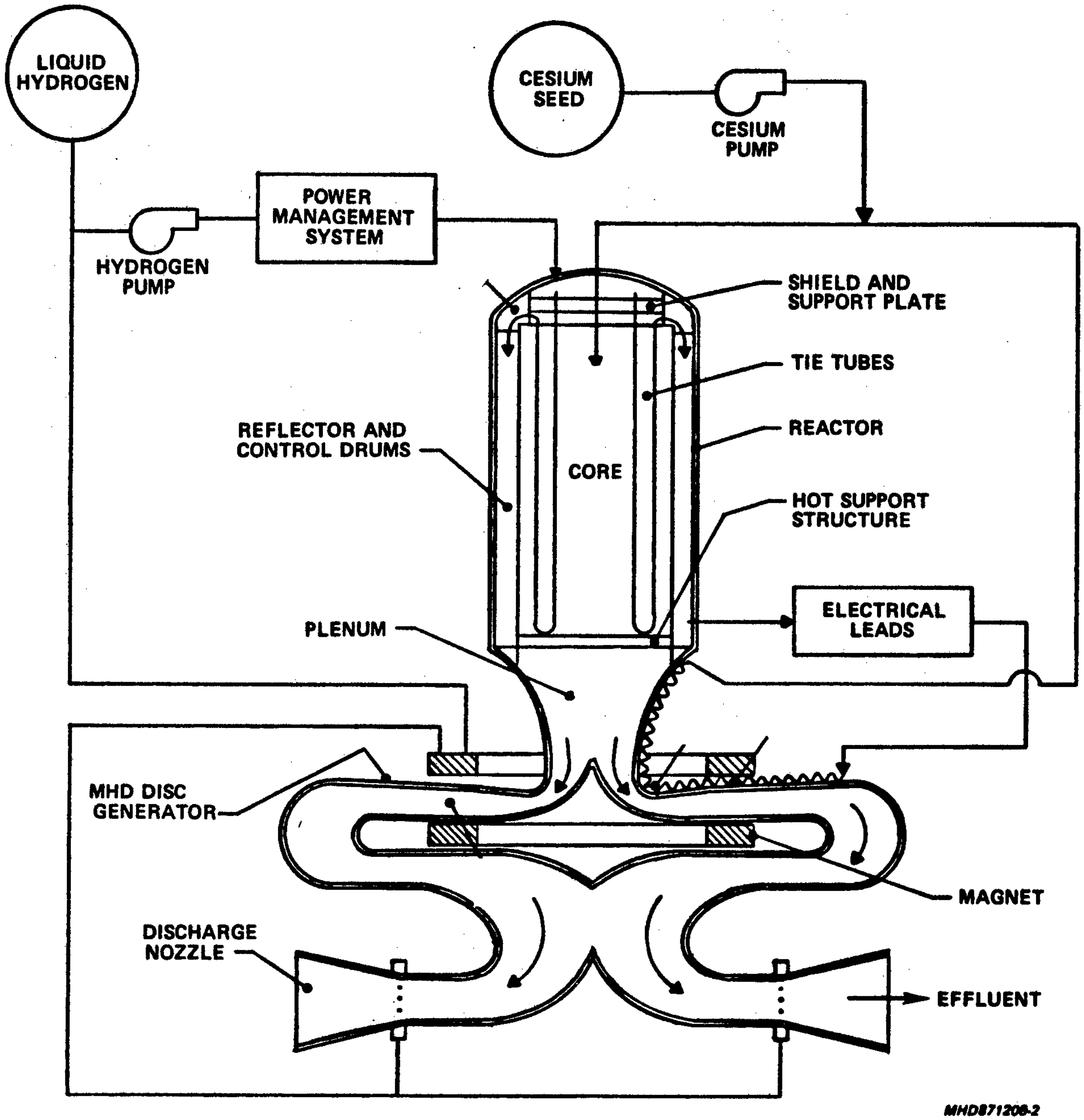

Figure 1-1. Overall MHD Power System Concept

considered for use in the Figure 1-1 power system as a design option, instead of the dedicated hydrogen supply. In operation, liquid hydrogen enters the system and cools the power conditioning subsystem, the reactor support structure, the MHD generator walls, and the reactor outlet nozzle walls. A separate hydrogen circuit is used to cool the magnet. A very low concentration cesium seed (about one third of a percent by weight) is added to the hydrogen before it enters the reactor inlet plenum. The reactor supplies the high temperature, lightly cesium seeded hydrogen to the MHD disk for electric power production in the generator. After power production, the gas leaves the disk generator through two exhaust nozzles which are diametrically opposed to minimize attitude control requirements.

The power system concept utilizes a NERVA (Nuclear Engine for Rocket Vehicle Application) derivative reactor. The NERVA/Rover reactor technology base is broad, encompassing successful testing of twenty reactors and innumerable components. That development program included one reactor, Pewee-1, which was very close in size and performance to the heat source required for this MHD power system. This combination of a hydrogen-cooled reactor and MHD disk generator permits a clean plasma that fully exploits nonequilibrium ionization at low concentrations of cesium in the working fluid. High conductivities result at levels an order of magnitude above thermal equilibrium values, permitting corresponding increases in generator power density and enthalpy extraction. Therefore, the disk configuration coupled with the NERVA derivative reactor is capable of substantial improvements in mass and size compared to chemically-driven MHD systems.

1.2 Functional Requirements

The space-based MHD power system concept shall be considered to power a generic, tube-type neutral particle beam (NPB) that requires semiannual testing. The generic load requirements are given in Figure 1-2.

This generic design shall have a lifetime of 10 years. The test mode will require about 100 s (20 cycles at 4 to 5 s each) of full power operation

Load voltage requirements: 100 kV

Number of tests: 20 cycles (startup/shutdown)

Test duration: Approximately 7 s

Test power level: 100 MW_e (A 2 to 3 s initial power level of 25 MW_e prior to the final 4 to 5 s of full power is desirable.)

Full power level: 100 MW_e (for 500 s, including tests)

Figure 1-2. Generic Load Requirements

over the 10 year life of the system. The battle burst mode will require an additional 400 s for a total requirement at full power of 500 s.

A duty cycle for the conceptual design is defined in order to specify electric power startup requirements and working fluid inventory (hydrogen/cesium) requirements for the conceptual design MHD power system. This duty cycle shall be as defined in Figure 1-3 and Figure 1-4.

Other system design objectives include the following:

- High reliability, because of the strategic importance of the SDI mission and the need for extended periods of operation or parking without access for maintenance or inspection

- Rapid responsiveness, covering rapid ramp-up to power and quick flexibility to variations in power demands

- Adaptability to specific power conditioning needs, to meet the differing requirements of the variety of weapon devices that might be energized by the MHD power system

- Adaptability to specific space platform configurations

- Utilize on-board fuels made available from other subsystems' disposals

- Free of disturbances to space platform stability, by avoidance of such perturbations as unbalanced thrust or internal machinery dynamics

- Compliance with all applicable nuclear safety criteria

- Survivability, both as regards the space environment as well as a hostile attack environment

OPERATING MODE OR TRANSITION	OPERATING TIME	MMW POWER SYSTEM POWER OUTPUT	MMW POWER SYSTEM POWER DEMAND[1]	TRANSITION TIME ALLOWED
Standby (or Station Keeping)	Continuous	0	30 kW_e (Average) 50 kW_e (Peak)	-
Standby to Ready Mode	-	0-25 MW_e	-	< 90 s
Ready	2-3 s	25 MW_e	-	-
Ready to Burst Mode	-	25-100 MW_e	-	< 1 s
Burst Mode[2] (Test/Semi-annual)	4-5 s	100 MW_e	-	~ 100 s[3]
Burst Mode	$\leq$ 400 s	100 MW_e	-	-

Notes: (1) Standby power demand shall be supplied by a solar or SP-100 nuclear power subsystem on-board the space platform.

(2) A semi-annual test is defined as a transition from the standby mode to the ready mode, operation at the 25 MW_e ready mode for 2 to 3 s, ramp up to full power (< 1 s), burst power operation for 4 to 5 s, then shutdown to the standby mode.

(3) Total semi-annual test duration from standby to full power to standby.

Figure 1-3. MMW Power System Duty Cycle Requirements

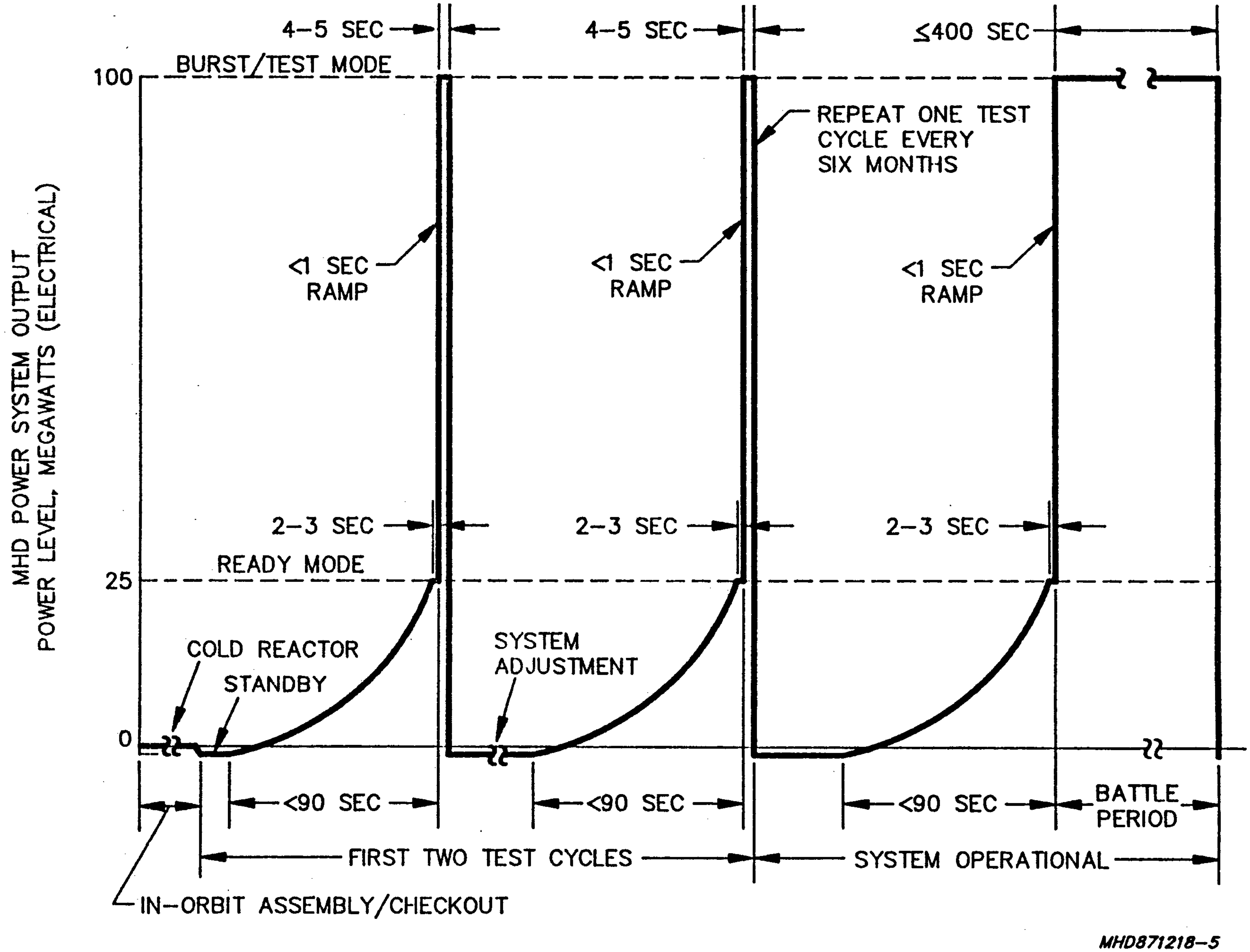

Figure 1-4. Load Profile Requirements

- Avoidance of harmful effluent effects which could damage/deteriorate/corrode materials, and interfere with command and control and weapon system/space platform operation.

1.3 Conceptual Design Scope

The conceptual design scope shall include all elements of the self contained MHD power system as listed in Figure 1-5. The scope of the conceptual design shall be consistent with the following:

- It is assumed that power from the MHD system will be conditioned and delivered to a dedicated weapon system electrical bus in the form of a specified direct current and voltage. Any power conditioning beyond the dedicated direct current electric bus is assumed to be within the weapon system design scope.

- It is assumed that appropriate power will be available for standby mode, ready mode, and burst mode from the space platform (SP-100 unit or other). Power requirements for these startup or maintenance conditions will be specified.

- All power system interfaces will be defined, but any other structures, components, or subsystems required to interface the MHD power system with weapons systems or space platforms of specific designs are outside the conceptual design scope. Requirements for these structures and components will be defined. Where generic requirements are inadequate, the load will be assumed to be a tube-type neutral particle beam discriminator/weapon.

- The reactor subsystem will be within the design and performance envelope of various NERVA derivative reactors (NDR) studied by Westinghouse for other related applications. Mass and size parametrics for the reactor plus any features that are unique to this specific application will be included. Nuclear safety

- MHD Power System

- Subsystems and Major Components

  - Reactor heat source (and shielding)
  - MHD disk generator
  - Magnet subsystem
  - Hydrogen supply subsystem
  - Seed supply subsystem
  - Power conditioning subsystem
  - Control subsystem
  - Effluent control subsystem
  - Emergency control and instrumentation subsystem

- Other Equipment

  - Power system structural members and components
  - Piping
  - Auxiliary power supplies
  - Auxiliary cooling equipment
  - Electrical/Busbars
  - Insulation

Figure 1-5. MHD Power System Conceptual Design Scope requirements for ground handling, launch, on-orbit operation, shutdown, emergency, abort, and disposal at the end of mission have been previously addressed in other studies and appropriate safety features incorporated in the NDR basic design. An evaluation of nuclear safety issues is outside the scope of this present study, except where unique safety requirements are determined to be necessary for developing the design.

- Technical issues related to the NDR will be defined within this study with emphasis on issues specific to the MHD disk application. It is assumed that any NDR development or test program costs will be funded within other separate programs.

1.4 Conceptual Design Objectives

Consistent with other requirements stated herein, the MHD power system shall be designed for minimum size and mass. The conceptual design shall be prepared to a level of detail that will permit gross system mass to be estimated within $\pm 20\%$. Justification of the parameters for the minimum size and mass point design shall be provided.

Schematic drawings of the integrated power system shall be prepared to show the following:

- the system component layout

- the method for integrating the power system with a space platform.

A description of the overall operation of the system and its major components shall be provided. The conceptual design and analysis shall provide, as a minimum, the following information for the total MHD power system:

- An overall power system energy balance including statepoint data such as fluid properties, flow rates, temperatures, pressures, and enthalpies for each operating mode so as to establish effects on other subsystems and the spacecraft operation.

- Power system thermal input

- MHD disk enthalpy extraction

- Net electric power generated

- Total system mass

- Total system dimensions

- Estimated power system cost (space system recurring production cost)

The conceptual design must include the identification and quantitative characterization of any dynamic loads, thrust vectors, and effluents produced by the power system. Startup and shutdown characteristics, including startup time, of the system must be considered, as well as steady-state operation. Standby, ready and burst mode system operating requirements and time required to switch from one mode to another shall be identified.

For the major components within the system design scope, the conceptual design information shall include the following:

- Component performance

- Component dimensions and weight and projections for other power levels

- Candidate materials of construction
- Estimated cost

The major components for this MHD power system are the:

- Reactor heat source (and shielding)
- MHD disk generator
- Magnet subsystem
- Hydrogen supply subsystem
- Seed supply subsystem
- Power conditioning subsystem
- Control subsystem
- Effluent control subsystem
- Emergency control and instrumentation subsystem

Justification shall be provided for assumed system and component values. For calculated values, information concerning the procedures and methods used shall be provided to permit an evaluation of the resulting values.

A preliminary analysis shall be made of the sensitivity of the significant parameters to identify scaling factors for smaller or larger electrical power systems.

A failure modes and effects analysis shall be made to guide the design of the system to identify where redundancy or improved design will be necessary to meet requirements.

2.0 SYSTEM REQUIREMENTS, GUIDELINES, AND INTERFACES

The flow path schematic and the statepoint data of Figure 2-1 comprises a power system meeting the performance requirements defined in subsequent sections of this document. The statepoint data of Figure 2-1 is preliminary and may change as a result of the System Parametric Studies. However, the Figure 2-1 data will serve as a basis for developing the design guidelines and establishing interface requirements for the subsystems.

2.1 Operational Requirements

The operational requirements include the performance, environmental, safety, command and control, and maintenance/resupply requirements for the MHD power system.

2.1.1 Performance Requirements

The power system shall produce direct current electrical power at the net rate of 100 MW_e for 500 s for a cumulative energy output of 50,000 MJ (5 x 10^{10}) consistent with the load requirements, duty cycle and load profile given in Figures 1-2, 1-3, and 1-4. The power system output of 100 MW_e shall be conditioned and delivered to a dedicated weapon system electrical bus at a direct current load voltage of 100 kV as specified in Figure 1-2. Quality of the power to be delivered shall be defined by the load requirements as to ripple, regulation, response time, interruption allowance, EMI, etc.

2.1.1.1 Power Transients

The system shall be capable of making the transition from the standby mode to the full power burst mode in 100 s or less. The transition from the standby mode to the ready mode shall take place in 90 s or less. In this transition, less than 25 kg of hydrogen shall be consumed. In the ready mode the system shall require less than 5.6 kg/s of hydrogen. During

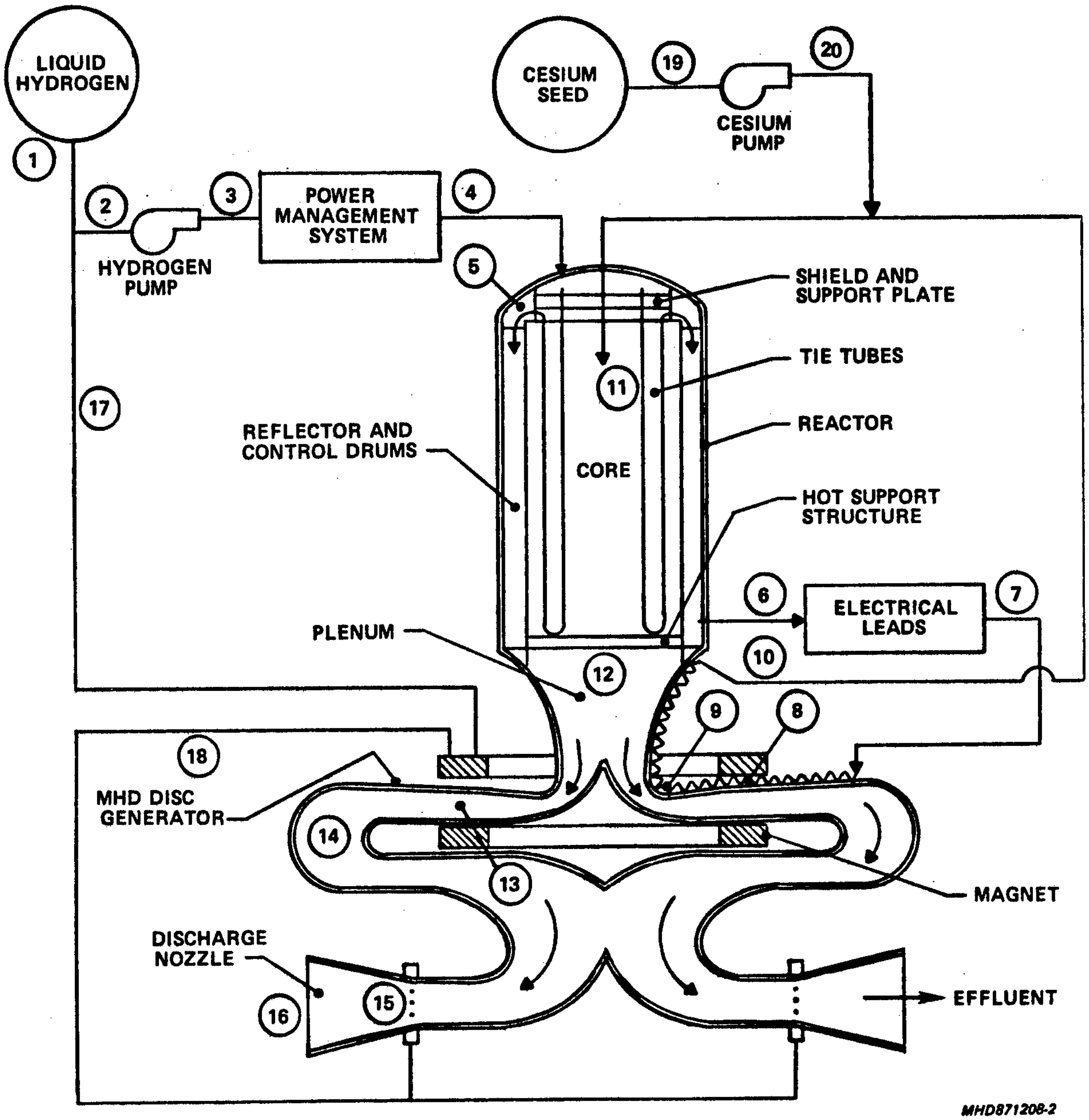

Figure 2-1. System Schematic and Statepoint Data

#	Location	C_s Mol Fr	W (kg/s)	P_{tot} (Atm)	T_{tot} (K)
1	H_2 Tank Outlet	0	5.530	1.00	20
2	H_2 Pump Inlet	0	5.452	1.00	20
3	Power Conditioning System Cooler Inlet	0	5.452	63.2	27
4	Core Support Structure Cooler Inlet	0	5.452	61.2	73
5	Reflector and Control Drum Cooler Inlet	0	5.452	51.2	413
6	Electrical Lead Cooling Inlet	0	5.452	46.6	532
7	2nd Section Disk Generator Cooler Inlet	0	5.452	45.6	567
8	1st Section Disk Generator Cooler Inlet	0	5.452	41.6	576
9	Reactor Lower Plenum Cooler Inlet	0	5.452	37.6	613
10	Seed Mixer Inlet	0	5.452	36.6	65
11	Reactor Core Inlet	5.0×10^{-5}	5.470	36.6	650
12	Disk Generator Inlet Nozzle	5.0×10^{-5}	5.470	16.6	2900
13	2nd Section Disk Generator Inlet	5.0×10^{-5}	5.470	0.71	2170
14	Thrust Vector Control Section Inlet	5.0×10^{-5}	5.470	0.25	1880
15	Exit Nozzle Inlet	4.9×10^{-5}	5.548	0.25	1850
16	Effluent Flow	4.9×10^{-5}	5.548		
17	Magnet Cooler Inlet	0.0	0.078	1.0	20
18	Effluent Thrust Vector Control Inlet	0.0	0.078	0.8	20
19	Cesium Pump Inlet	1.0	0.018	1.0	650
20	Seed Mixer Inlet	1.0	0.018	50	679

Figure 2-1. System Schematic and Statepoint Data (Continued)

operation, the system shall be capable of responding to transients with periods of 5 s. Startup and maintenance power for standby shall be provided by other power sources assumed to be available on the space platform. All instrumentation and control power associated with the safety of the reactor power system shall be supplied by an independent, uninterruptible power source, such as an electrochemical battery that is continuously being recharged during dormant non-use periods.

2.1.1.2 Design Lifetime/Operating Cycles

The power system shall have a space storage lifetime capability of 10 years. Test, standby, ready, and burst mode duty cycles shall be as defined in Section 1.2, "Functional Requirements."

2.1.1.3 Availability/Reliability

The system mission reliability goal shall exceed 0.95.

2.1.2 Environmental Requirements

The environmental requirements applicable to the MHD power system include those due to the launch environment, the space environment, and the hostile threat environment.

2.1.2.1 Launch Environment Requirements

The launch environment thermal and dynamic envelope the MHD power system will be subjected to is defined in Appendix C for the Shuttle Orbiter. All launching, on-orbit, de-orbit and loading values are given in Appendix C in the event that the MHD power systems must be returned to earth for any reason. The launch environment for launch vehicles other than the Shuttle Orbiter is TBD.

2.1.2.2 Space Environment Requirements

The MHD power system ion space will encounter a variety of natural and man-made environmental conditions. The most critical threats in this category are man-made space debris and meteoroids. Survivability from the first can be achieved by placing the power system in an orbit predetermined to be relatively free of encounters with existing space debris. Survivability from the latter is a design requirement. Micrometeoroid damage is of greatest concern in the design of the tankage and piping components, and this factor must be taken into account in the design. A more detailed total system design must also include consideration of protection for the nuclear reactor and the remaining subsystems. Additional environmental factors that impact the design include natural radiation, space plasma, maneuverability and payload interactions. All of the above environment requirements are specified in Appendix A.

2.1.2.3 Hostile Threat Environment

Designing for survivability from hostile weapon threats requires significant detailed analyses and design efforts which are not possible within the resources of the present contract. These analyses must take into consideration the different types of weapons that may be encountered, including lasers, neutral particle beams and chemical rockets. The magnitudes of the weapon effects in terms of impact size, impact energy, impacting mass must be assumed and the degree of damage analyzed. Designs for countering the threats must be then developed. Designs could take the form of passive or active protection. The first consists of armoring (against neutral beam particles) appropriate coatings to deflect laser beams, etc., while the latter may consist of evasive maneuvers such as rotational motions to reduce the energy absorption on and near the surface of the targetted area(s).

Since the hostile threat environment is classified (secret) and cannot be defined for this contract, it would be appropriate to define the limits and capability of the MHD system design concepts. These would then be submitted for review to an organization that could evaluate whether the design is capable of withstanding the parameters defined in the classified documents. Parameters to be defined are as shown below.

Effect	Magnitude	Duration
Acceleration	TBD	TBD
Debris	TBD	TBD
Neutron Flux	TBD	TBD
Gamma Flux	TBD	TBD
Thermal Radiation	TBD	TBD
EMP	N/A	N/A

2.1.3 Safety

The purpose of this section to identify specific safety design requirements consistent with those defined in Reference (1).

At this early conceptual stage of the MHD power system development, however, it is essential to focus on the safety aspects of the system to ensure that critical safety issues are identified and resolved as the engineering design progresses. Detailed safety analysis and design of the nuclear reactor are well beyond the scope of the present contract. However, safety issues related to NERVA Derivative Reactor applications are being considered in other programs funded by the U. S. Department of Energy. Where appropriate, Westinghouse will use the results from these associated programs to guide the conceptual design of the MHD power system. The following paragraphs present the major General Design and Mission (GD&M) requirements from Reference (1) and an assessment of the NDR compliance to each requirement.

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(1) "Nuclear SAfety Criteria and Specifications for Space Nuclear Reactors," U. S. Department of Energy, Office of Space Nuclear Projects, August 1982.

SAFETY DESIGN REQUIREMENTS

The stated policy of the United States, for all U.S. nuclear power sources in space, "is to ensure that the probability of release of radioactive material and the amounts released are such that an undue risk is not presented, considering the benefits of the mission"*. The objective of Reference (1) to provide safety criteria to ensure that the design is acceptable from a radiological safety standpoint. Reference (1) defines specific safety design requirements for the SP-100 Space Nuclear Reactor Power Technology Program. However, these design requirements are sufficiently generic in nature to be equally applicable to any nuclear power source for space application. The following major GD&M requirements are considered necessary but not sufficient in order to comply:

GD&M No. 1

The reactor shall be designed to remain subcritical if immersed in water or other fluids (such as rocket propellants) to which it may be exposed.

Design Compliance

Immersion of the NDR core in water or other moderating substances significantly alters the core nuclear characteristics. Assuming that the

*The U.S. approach to nuclear safety has been spelled out in a number of documents, e.g., 10CFR20 notes that in accordance with recommendations of the Federal Radiation Council, approved by the President, persons engaged in licensed activities should "make every reasonable effort to maintain radiation exposures, and releases of radioactive materials in effluents to unrestricted areas, as low as is reasonably achievable" taking into account the state of technology and the economics of improvement and other factors. DOE Order 5480.1A states that it is the policy of the DOE to "assure protection of the environment, the safety and health of the public, and Government property against accidental loss and damage." In a U.S. working paper submitted to the U.N. Working Group on the Use of Nuclear Power Sources in Outer Space (Paper A/AC.105/C.1/WG.V/L.8, dated 23 January 1980), it is stated that "the primary safety design objective is to minimize the potential interactions of the radioactive materials with the populace and the environments so that exposure levels are within limits established by international standards."

voids in the reactor core are flooded with water upon immersion, the core reactivity would increase. Considerable effort was expended in studying this safety issue in the NERVA program. Several options were defined to assure subcritical conditions on launch alert or subsequent core immersion scenarios. The control rod system designed for normal operational control cannot suppress the amount of excess reactivity associated with a water immersion. Consequently, an anti-criticality poison system is required for the NDR design. A tentative poison concept consists of poison wires containing fully enriched B10. The wires are inserted into two coolant channels in each fuel element and are in place during assembly and transport of the NDR. Once stable orbit is achieved and just prior to operational startup, the wires would be removed from the core.

GD&M No. 2

The reactor shall have a significantly effective negative power coefficient of reactivity.

Design Compliance

The power coefficient for the NDR core is sufficiently negative to guarantee safe and stable operation. Since fully enriched uranium fuel is employed in the design, the fuel Doppler coefficient is small. Fuel Doppler feedback is derived from the broadening of U238 absorption resonances with temperature. However, the NDR core thermal expansion coefficients are expected to provide sufficiently large, fast acting, negative reactivity feedback with increasing core temperature to ensure safe and stable operation.

GD&M No. 3

The reactor shall be designed so that no credible launch pad accident, range safety destruct actions, ascent abort or reentry from space resulting in Earth impact could result in a critical or supercritical geometry.

Design Compliance

The possibility of core compaction caused by explosion or launch abort impacts exists. Core compaction of the NDR fuel region is not as severe a condition as that of water immersion. Assuming that a compaction accident compresses the core uniformly eliminating all void regions, the core reactivity is assumed to increase. Consequently, the poison wire system, necessary for water immersion case, will be designed to ensure subcriticality in the event of core compaction. It should be noted that a combination of immersion and partial core compaction would entail less reactivity worth, since some compaction reduces the amount of water which can enter the core region, and therefore, neutron moderation will be less effective.

Critical or supercritical geometry due to terrestrial immersion or compaction following reactor operation will be avoided by establishing a stable orbit for power operation of the NDR. A stable, inherently long lived, orbit will provide sufficient time to either: 1) boost the NDR to a higher, still longer lived orbit, 2) using on-board thrust capacity, move the system to solar orbit, 3) remotely retrieve the power system for controlled earth return in a reentry vehicle designed for this purpose or preferably, or 4) maintain the core intact under passive decay heat removal for the lifetime of the orbit.

It is not expected that any over-pressure or high temperatures from an explosion would have significant effect on the normal shutdown system or the core configuration. The poison wire system is sufficient to maintain core subcriticality even with full rod ejection. Breakup of the core as the result of an explosion would enhance subcriticality. Considering the high temperature requirements for the materials of construction of the reactor, the reactor should be resistant to long term fire effects. Substantial high temperatures would lead to loss of core geometry which would increase subcriticality. Meltdown and pooling of the fuel material to form a critical mass is highly unlikely under these conditions.

GD&M No. 4

The reactor shall not be operated (except for zero power testing yielding negligible radioactivity at the time of launch) until a stable orbit or flight path is achieved and must have a reboost capability from low earth orbit if it is operated in that orbit.

Design Compliance

The NDR will not be operated at power until the power system has reached stable orbit and has been deployed and the orbital parameters confirmed. No pre-launch power operations of the reactor are contemplated, other than zero power testing of control and safety systems. Emplacement of the poison wire system prior to delivery to the launch site will ensure that inadvertent operation of the control system will not result in a power ramp of the reactor. The poison wire system has sufficient negative reactivity to maintain the core in a subcritical condition even though the primary control system has been withdrawn. Withdrawal of the poison wire system will not occur until a stable orbit is confirmed, and preliminary safety checks of the system have been made and confirmed.

In addition, the design of the reactor control system will include multiple control actuators armed with interlocks and brakes to preclude inadvertent rod withdrawal. Each actuator will have redundant controls and operating mechanisms requiring several commands for operation.

GD&M No. 5

Two independent systems shall be provided to reduce reactivity to a subcritical state. They shall not be subject to common cause failure.

Design Compliance

The NDR core design incorporates two independent translational (insertion) shutdown systems for operational control. The two systems consist of a primary and secondary control bank analogous to that used in more conventional terrestrial reactor plants. The systems are independent and each system contains sufficient worth to shutdown the reactor at any time during the operational lifetime of the reactor. The primary system is used to provide additional burnup reactivity control as well. Although specific assignments of individual control rods to either the primary or secondary systems have not yet been made, the system worth, including uncertainties, is sufficient to permit some flexibility in these assignments once detailed design calculations have been performed.

GD&M No. 6

The reactor shall be designed to ensure that there is an independent shutdown heat removal system or independent heat removal paths within the heat transport system to provide decay heat removal.

Design Compliance

The NDR and the MHD power system shall be designed to provide active cooling of the reactor, using on-board hydrogen, following continuous operation at the design power level for the entire design burst power duration.

GD&M No. 7

The unirradiated fuel shall pose no significant environmental hazard.

Design Compliance

The NDR fuel design utilizes the coated composite uranium fuel matrix developed for the original NERVA program. Use of this type of fissile material rather than the use of plutonium will greatly minimize the potential for a release of unirradiated fuel to the environment.

GD&M No. 8

Toxic material releases and dispersal shall pose no significant environmental hazard.

Design Compliance

The NDR is designed to minimize the potential for release or dispersal of toxic materials to the environment. The only potentially toxic material identified in the design of the NDR prior to operation is beryllium. Analyses will be carried out to determine the toxic hazards associated with release of beryllium during the initial phases (transportation, prelaunch and launch/ascent) of the mission.

2.1.4 Command and Control Requirements

(To be Determined)

2.1.5 Maintenance/Resupply Requirements

(To be Determined)

2.2 System Interface Requirements

The MHD power system design must satisfy the functional and operational requirements of Section 1.2 and 2.1. In addition, the power system design must address the top-level system interactions discussed in Section 2.3. This section is focused on the physical interface requirements between the MHD power system and the space platform which includes the weapon systems. Other power system physical interfaces are mission-dependent and are associated with the launch vehicle and on-orbit installation of the power system in the space platform. The power system interface requirements will be specified by Interface Control Drawings (ICDs) that will be used to define and control the structural, piping, electrical, control, and instrumentation requirements. The power system subsystem and major component interfaces will be controlled by similar, lower level ICDs as described in Section 3.0, Subsystem Requirements, Guidelines and Interfaces. The ICDs, when completed, will include tabular data specifying the dimensions, materials, and other characteristics of each interface.

2.2.1 Space Platform Interfaces

The configuration interface between the space platform and the MHD power system is represented by a plane defined as the end of a conical adapter. The center of gravity of the power system will be located on an axis normal to this plane which passes through the center axis of the conical adapter. At any operating condition, the power system shall produce:

- less than (TBD) N thrust along the axis
- less than (TBD) N thrust normal to the axis
- less than (TBD) Nm torque normal to the axis

The power system shall be designed to minimize or cancel the thrusts and torques by using opposing forces.

Radiation dose shielding for the MHD power system shall be designed in accordance with the criteria specified in Appendix A, Section A.8, Payload Interaction with reactor to power conditioning and reactor to payload separation distances as specified in Figure 2-2. Local or global radiation shielding, or combinations thereof, may be used.

For configurations where the space platform onboard, base electrical power system is supplied by a nuclear reactor (e.g., SP-100) or other type of power unit, the MHD power system reactor shall be placed and shielded so as to avoid degradation of the base electrical power system sensitive components (e.g., thermoelectric converter units, power conditioning electronics, and instrumentation sensors and electronics).

During operation of the space platform and weapon system, vibration, lateral acceleration, axial acceleration, and angular acceleration will be imposed on the MHD power system. The magnitude of these effects is (TBD).

The MHD power system to space platform/weapon system interfaces are detailed in Figure 2-3.

2.2.2 Launch Vehicle Interfaces

There are several possible scenarios, using different launch vehicles, to lift the MHD power system into orbit. If the power system is launched into orbit with cryogenic hydrogen in its dedicated supply tank, an unmanned booster of sufficient payload capacity must be used. If the hydrogen tank is empty or launched independently of the power system, either an unmanned booster or the shuttle orbiter may be used.

If the shuttle orbiter is used for launch, the MHD power system design must be in compliance with the structural interfaces, loads, vibration, accelerations, and other environmental constraints and requirements specified in Appendix C, Shuttle Orbiter/Cargo Bay Interface Data.

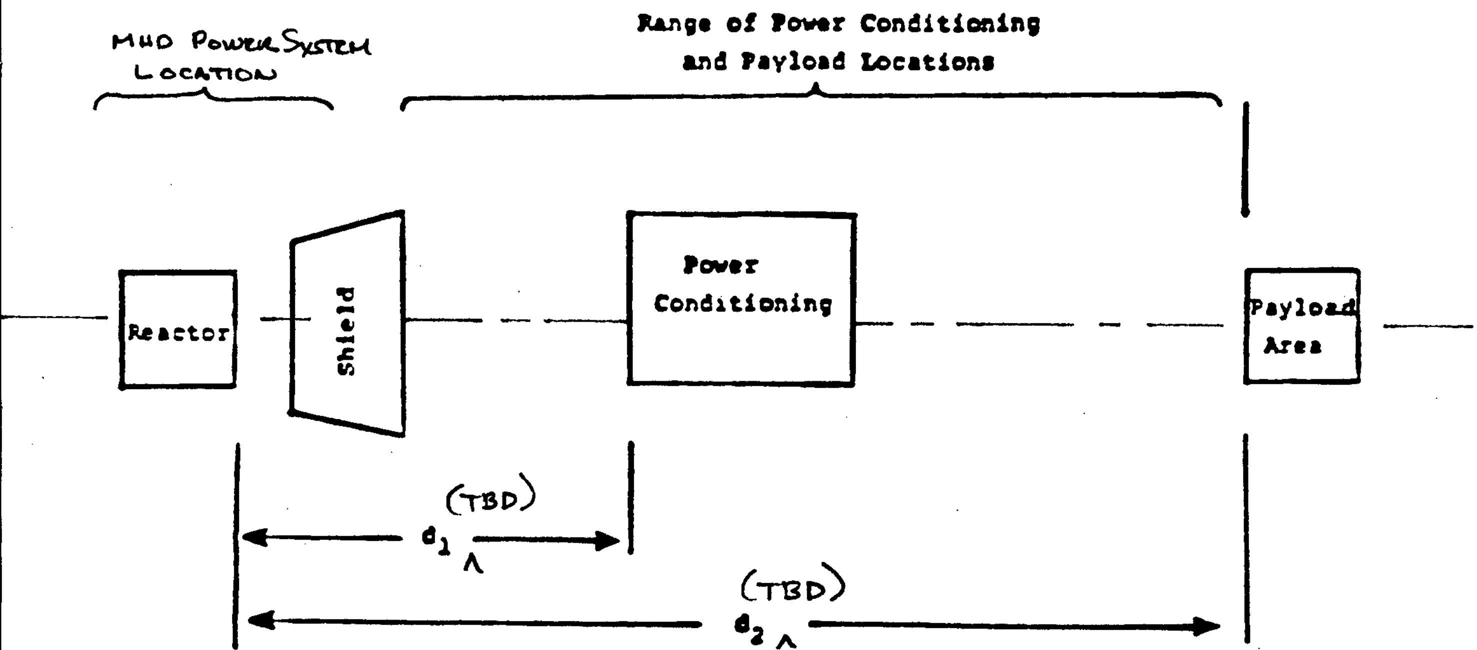

Figure 2-2. Reactor Separation Distances

(TBD)

Figure 2-3. MHD Power System to Space Platform/Weapon System Interfaces ICD

The MHD power system to Shuttle Orbiter interfaces are detailed in Figure 2-4. Interfaces with other launch vehicles are (TBD).

2.2.3 Installation/Other Interfaces

Removal of the MHD power system from the Shuttle orbiter or an unmanned launch vehicle and installation on the space platform will require interfacing with robotic systems, the Orbital Maneuvering Vehicle (OMV) and other equipment. While the OMV is under development, scenarios must be developed for the removal and installation of the MHD power system before the equipment needs and interfaces can be specified. Therefore, only a preliminary definition of the power system interfaces with the OMV is appropriate at this time. OMV/MHD Power System interfaces are specified in Figure 2-5.

2.3 System Synergism and Interactions

The MHD power system concept has unique characteristics that can yield synergistic benefits when integrated with the weapon system and/or have potential interactive impacts on the weapon system and space platform. These subjects are discussed in the following subsections.

2.3.1 Synergism

The NERVA reactor was originally designed to use hydrogen as the reactor coolant and as the propellant. Therefore, the use of hydrogen in the NDR/MHD system for burst power production is a natural application of the NERVA technology. However, a more important aspect related to this coolant is the potential synergism this provides between the weapon system and the electric power source. This synergism arises as a result of the potentially large amount of hydrogen available at a low temperature from the weapon system, where it is used for thermal stabilization. All of the candidate weapon systems currently under consideration require large amounts of low temperature cooling during weapon operation. Cryogenic hydrogen cooling has

(TBD)

Figure 2-4. MHD Power System to Shuttle Orbiter/Cargo Bay Interfaces ICD

(TBD)

Figure 2-5. MHD Power System to OMV Interfaces ICD been determined to be the most mass effective approach. It has been shown that this synergism can result in a significant reduction in overall weapon-power system mass. Since the hydrogen is available, it is both realistic and desirable to consider the MHD power system design integrated with the weapon system. Hydrogen supply as an alternate to providing a dedicated hydrogen supply for the power system.

The open-cycle MHD power system for burst power offers opportunities for synergism in other ways. They include orbital transfer, orbital corrections, attitude control, and post-mission disposal. It is conceivable to design the MHD disk exhaust nozzles to provide flexible maneuvering thrust to serve the above functions. Mass savings may be possible from these synergisms. These possibilities will require substantial detailed design and analysis be performed later in conjunction with specific missions and with the overall space platform design.

2.3.2 Interactions

The characteristics of the MHD power system may cause interactive impacts on the weapon system, when the impacts result from torque, vibration, thrust vectors, and effluents. The weapon systems considered for SDI applications have stringent requirements on pointing, targeting, slewing rates and on allowed jitter. Consequently, the dynamic loads, shock and thrust loads are of significant concern. These impacts are discussed in the following subsections.

One approach to the alleviation of the adverse impacts expected is to design for a tethered power source. However, this approach may introduce other control and large mass penalties that result from the tether, longer power transmission lines, and added control requirements. Overall space platform and mission-specific design considerations and trade-off studies can resolve the issues related to the impacts discussed below.

2.3.2.1 Torque

Rotating pumps produce torque and gyroscopic moments. The use of counter-rotating units properly positioned can reduce these effects to controllable levels. Also, fluid flow dynamics affect moments and forces that react with these components to cause rotations or oscillations.

2.3.2.2 Vibration

Vibration can be expected from several sources: It can arise from the flow conditions and forces within the MHD disk generator, from imbalances in the loads on counter-rotating pumps and from imbalances of flow conditions and in the thrusts from the exhaust nozzles during burst mode operation. Wide ranges of vibration frequencies are expected. The control of the vibrations to acceptable levels requires careful, detailed overall spacecraft design, with consideration of the specific mission operational requirements and constraints. Internal damping and other design approaches that have a long precedent in other engineering applications can be used.

2.3.2.3 Thrust Vectors

The open-cycle MHD power system operation can produce significant thrust. The thrust vector is largely cancelled by the use of exhaust nozzles in opposing pairs that null out the thrust. However, some thrust imbalances will be encountered. Experiences with liquid and solid propellant rockets have shown that pairs of rockets operating simultaneously can hold this imbalance to approximately 1% of the thrust. Consequently, pairs of opposing nozzles can be used to minimize the thrust imbalance. Thrust imbalance could also be controlled by designing the MHD disk generator exit nozzles with active automatic flow control devices (e.g., fluidic controls). Any remaining thrust imbalance could also be cancelled through the use of small space platform control thrusters.

2.3.2.4 Shock Loads

Flow dynamic and external thrusting shock loads are expected during the startup of the burst mode of operation. These loads will impact the design, size and mass of the exhaust nozzles. More detailed designs and analyses are needed to evaluate this effect and its impact on the total system mass.

2.3.2.5 Electrical Noise/Magnetic Fields

Operation of the MHD disk generator and the associated magnet, power conditioning, and control subsystems will produce an electromagnetic noise spectrum that can potentially affect the functioning of space platform and weapon system communication, control, and electrical functions. The electromagnetic noise from the MHD power system and the electromagnetic field (dipole moment and rise time) due to the magnet subsystem must be characterized and interference with other mission functions prevented by appropriate shielding, separation, configuration arrangements, and/or design features within the MHD power system.

2.3.2.6 Effluent Effects

The MHD open-cycle system produces an effluent consisting of hydrogen gas seeded with cesium. In addition to thrust effects, the effluent must not interfere with the control, aiming, pointing, power operation, and other functions of the weapon system and space platform. Acceptable limits for tolerance (or non-tolerance) of the effluents must be defined for the specific weapon system and appropriate power system design approaches used to insure compliance. The design approaches that could be considered are: minimization of the effluent produced, control of the effluent constituents such as recovery of the cesium seed before or after exhausting through the nozzles, pointing the exhaust nozzles away from critical areas of the space platform, the use of other configuration arrangements, and physical separation between the MHD power system and its exhaust nozzles and the remainder of the space platform.

The combined effects of the effluent from the MHD power system and the hydrogen effluent from the weapon system thermal control and differences in the effluent produced (e.g., temperature difference, cesium seed concentration) must also be considered.

3.0 SUBSYSTEM REQUIREMENTS, GUIDELINES, AND INTERFACES

The following sections document the subsystem requirements, guidelines and interfaces. Each subsystem is described in terms of the following format:

- Scope and Functional Description
- Interface Requirements
    - Process Interfaces
    - Weapon System Interfaces
    - Space Platform Interfaces
    - Launch Vehicle Interfaces
    - Installation/Other Interfaces
- Design Requirements and Guidelines
    - Performance Requirements
    - Design Life/Operating Cycles
    - Availability/Reliability
    - Environmental Requirements
    - Configuration Requirements
    - Structural/Materials Requirements
    - Synergism/Interaction Requirements
    - Safety Requirements
    - Command and Control Requirements
    - Maintenance/Resupply Requirements
- Reference/Applicable Documents

The above is consistent with the overall system requirements, guidelines and interfaces format. When subsystem requirements are the same as the system level requirements, they will be incorporated by reference.

Interface requirements will be defined in the form of Interface Control Drawings (ICDs), including tabular data as necessary, to specify the physical interfaces for each subsystem. Input/output statepoint data for subsystem process interfaces shall be consistent with the overall system process statepoints defined in Figure 2-1. The interfaces for all of the major components of the system, listed below, will be defined by separate ICDs.

- Reactor heat source (and shielding)
- MHD disk generator
- Magnet subsystem
- Hydrogen supply subsystem
- Seed supply subsystem
- Power conditioning subsystem
- Control subsystem
- Effluent control subsystem
- Emergency control and instrumentation subsystem

3.1 Reactor Heat Source (and Shielding)

SCOPE AND FUNCTIONAL DESCRIPTION

Scope: The developed technology of the demonstrated NERVA derivative (NDR) nuclear reactor is selected for the hydrogen plasma heat source. The technology issues and any development efforts associated with the selected technology nuclear subsystem are addressed in other programs and not treated within the scope of this effort. The technology requirements currently available are identified for use in defining the system concept described herein.

Functional Description: The NERVA derivative reactor concept incorporates a solid core, graphite and zirconium hydride moderated epithermal reactor employing an open loop, hydrogen-cooled disk MHD power conversion system. The NERVA derivative reactor data is presented in Appendix B.

In addition to overall performance goals, identified in Section 2.0, System Requirements, the reactor must meet specified general safety criteria. The core concepts must demonstrate a negative power coefficient to assure stability and must remain subcritical in all accident conditions including immersion in water or core compaction resulting from accidents during transport or launch. Two independent shutdown systems are also be included to assure safe shutdown from all operational states. These functional requirements must be achieved within the overall system constraint of minimum total system mass.

The tie tube support system provides the NDRs with the second independent means for decay heat removal. In the event of reactor shutdown, hydrogen is used to remove the decay heat through the normal flow path under this condition. The hydrogen flow is pulsed to provide long term decay heat removal when the afterheat has decayed to relatively low levels. In the event that the normal flow path cannot be utilized, the tie tube support system and the secondary heat removal system are used to removed decay heat.

The nuclear design basis and functional requirements established for the multimegawatt space power system have a significant impact on the reactor design. Of primary consideration are the reactor power level and operational lifetime. For analysis, an integrated power level of (TBD) MW-YR has been assumed for the base design calculations. To investigate the sensitivity of the design to integrate power levels, a range from ___ to __ MW-YR is to be evaluated.

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-1. Reactor Heat Source (and Shielding) ICD

3.2 MHD Disk Generator

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-2. MHD Disk Generator ICD

3.3 Magnet Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-3. Magnet Subsystem ICD

3.4 <u>Hydrogen Supply Subsystem</u>

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-4. Hydrogen Supply Subsystem ICD

3.5 Seed Supply Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-5. Seed Supply Subsystem ICD

3.6 Power Conditioning Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-6. Power Conditioning Subsystem ICD

3.7 Control Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-7. Control Subsystem ICD

3.8 Effluent Control Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-8. Effluent Control Subsystem ICD

3.9 Emergency Control and Instrumentation Subsystem

SCOPE AND FUNCTIONAL DESCRIPTION

INTERFACE REQUIREMENTS

DESIGN REQUIREMENTS AND GUIDELINES

REFERENCES/APPLICABLE DOCUMENTS

(TBD)

Figure 3-9. Emergency Control and Instrumentation Subsystem ICD

4.0 ANALYTICAL REQUIREMENTS

4.1 Computer Codes

Where appropriate, all analysis shall be performed using presently available Westinghouse proprietary computer codes which have well documented performance histories. Modifications of these codes to incorporate the special characteristics of the MHD power system have been made as required. The basis for these modifications shall be documented and reported in order to permit evaluation of the suitability of the modifications. Special purpose codes needed to perform necessary analytical tasks which are not presently available will be developed as required, and the algorithms and assumptions utilized will be documented.

4.2 Working Fluid and Materials Properties

The values of material properties used for the analysis shall be derived from demonstrately reliable sources. In these cases where curve fits to available property data are used to simplify calculations, or to extrapolate data, the equations used will be documented, and the accuracy of the fit over the appropriate range will be verified.

- The basis for fluid properties will be the "Tran 72" proprietary code
- The basis of metallic, graphite, and ceramic structural and thermal properties shall be TBD
- The Materials Properties Data Book (NERVA program)
- The basis of composite structural and thermal properties shall be TBD

4.3 Assessment of Environmental Input

In evaluating the reliability of the system over the design lifetime, the following criteria shall be used:

Meteroid penetration risk: TBD

Space and weapons debris penetration risk: TBD

EMP effects on system integrity: TBD

Thermal radiation effect on thermal integrity: TBD

As the system is reactor-driven, the effects of environmental neutrons and gamma radiation on the system are expected to be small relative to the self-induced effects. The effects on weapons-induced fluxes will be evaluated using the same techniques used to evaluate the self-induced fluxes. The effect of the shock and vibration loads induced by weapons operation will be evaluated using standard structural analysis techniques.

5.0 APPLICABLE DOCUMENTS

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"Nuclear Safety Criteria and Specifications for Space Nuclear Reactors," U.S. Department of Energy, Office of Space Nuclear Projects, August 1982.

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Space Nuclear Power Systems 1984, Proceedings of the First Symposium on Space Nuclear Power Systems, Vol. I, "Safety Considerations for the Use of Nuclear Power in Space," Duance C. Sewell, January 1984.

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APPENDIX A

ENVIRONMENTAL REQUIREMENTS

APPENDIX A

ENVIRONMENTAL REQUIREMENTS

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APPENDIX A - ENVIRONMENTAL REQUIREMENTS

A.1 Introduction

The prime power system (power source and the power conditioning subsystems) must be designed to be tolerant of the following environment. [Ref. 13].

A.2 Natural Radiation

Determination of natural environment radiation levels for the SDI-mission spacecraft shall employ the following models:

- NASA Model AP-8
  Trapped Protons Environment for Solar Maximum and Solar Minimum (U)
  NSSDC 76-06, December 1976

- NASA Model AE-5
  A Modeled Environment of Trapped Electrons for Solar Maximum (Inner Zone) (U) NSSDC 72-10, November 1972

- NASA Model AEI-7
  A Modeled Environment of Trapped Electrons for Solar Maximum (Outer Zone) (U) To be Published

The data of Figures A-1 through A-3 highlight levels of geomagnetically trapped electrons, geomagnetically trapped protons, and solar flare protons, respectively.

A.3 Meteoroids

The power system shall operate while in a meteorite environment as specified for a 6000 km orbit by NASA SP-8013.

Omnidirectional Integral Fluxes Based on NASA
Models AEI-7Hi and AE-5 Where Applicable

Energy (E) MeV	Electrons/cm²-Day (>E) LEO	MEO	GEO
0.05	3.28E 10	1.76E 12	2.56E 12
0.25	6.85E 09	6.71E 11	8.52E 11
0.50	2.34E 09	3.29E 11	2.84E 11
0.75	1.41E 09	2.18E 11	1.31E 11
1.00	9.26E 08	1.46E 11	6.02E 10
1.25	6.57E 08	1.01E 11	2.92E 10
1.50	4.71E 08	7.01E 10	1.42E 10
1.75	3.42E 08	4.90E 10	6.90E 09
2.00	2.51E 08	3.44E 10	3.35E 09
2.25	1.92E 08	2.60E 10	1.76E 09
2.50	1.48E 08	1.97E 10	9.27E 08
2.75	1.12E 08	1.50E 10	4.88E 08
3.00	8.62E 07	1.14E 10	2.57E 08
3.25	6.92E 07	9.37E 09	1.90E 08
3.50	5.59E 07	7.73E 09	1.41E 08
3.75	4.53E 07	6.38E 09	1.04E 08
4.00	3.68E 07	5.27E 09	7.70E 07
4.25	2.59E 07	3.61E 09	5.14E 07
4.50	1.82E 07	2.48E 09	3.44E 07
4.75	1.29E 07	1.70E 09	2.30E 07
5.00	9.07E 06	1.16E 09	1.54E 07
5.25	4.94E 06	6.31E 08	8.12E 06
5.50	2.69E 06	3.43E 08	4.29E 06
5.75	1.47E 06	1.86E 08	2.27E 06
6.00	8.00E 05	1.01E 08	1.20E 06
6.25	2.41E 05	3.11E 07	3.22E 05
6.50	7.12E 04	9.64E 06	0.0
6.75	1.99E 04	5.93E 05	0.0
7.00	0.0	0.0	0.0
7.25	0.0	0.0	0.0

Figure A-1. Geomagnetically Trapped Electrons

Omnidirectional Integral Fluxes Based on NASA Models AP-8

Energy (E) MeV	Protons/cm^2-Day (>E) LEO	MEO	GEO
0.01	1.36E 09	3.62E 12	3.20E 11
0.05	9.96E 08	2.73E 12	1.84E 11
0.10	7.05E 08	1.95E 12	9.19E 10
0.25	3.24E 08	7.68E 11	3.45E 10
0.50	1.48E 08	1.91E 11	1.67E 09
1.00	7.03E 07	1.39E 10	2.24E 07
2.00	4.18E 07	1.15E 08	0.0
5.00	2.58E 07	4.27E 04	0.0
10.00	1.95E 07	0.0	0.0
20.00	1.57E 07	0.0	0.0
30.00	1.40E 07	0.0	0.0
40.00	1.27E 07	0.0	0.0
50.00	1.16E 07	0.0	0.0
95.00	7.49E 06	0.0	0.0
100.00	7.14E 06	0.0	0.0
150.00	4.30E 06	0.0	0.0
200.00	2.62E 06	0.0	0.0
250.00	1.61E 06	0.0	0.0
300.00	9.99E 05	0.0	0.0

Figure A-2. Geomagnetically Trapped Protons

Omnidirectional Integral Fluence Based On An Estimate for the 1988-1992 Time Period

Proton Energy (E) MeV	Fluence-Protons/cm²-Yr (>E) LEO	MEO	GEO
1	3.0E 10	7.3E 10	9.0E 10
5	1.3E 10	3.0E 10	3.8E 10
10	6.7E 09	1.6E 10	2.0E 10
30	1.9E 09	4.5E 09	5.6E 09
50	8.7E 08	2.1E 09	2.6E 09
100	2.0E 08	4.8E 08	6.0E 08
200	1.5E 07	3.6E 07	4.5E 07

NOTES:

1. For mission lifetimes longer than three years the integrated exposure shall not exceed three times the yearly values given.
2. Peak flux levels (particles/sq-cm-sec) during a large solar proton event shall be taken as 8.0×10^{-6} of the yearly values given.
3. The solar flare alpha particle environment shall be assumed to be ten percent of the proton fluence.

Figure A-3. Solar Flare Protons

A.4 Space Debris

The power system shall operate while in the space debris environment specified in Figure A-4. Debris shall be assumed to consist of spherical fragments of aluminum impacting the spacecraft at a relative speed of 10 km/sec.

A.5 Space Plasma

The Earth's plasma is characterized as shown in Figures A-5 and A-6. Design concepts of the nuclear reactor MHD electrical power system shall include capability to operate in the plasma environment without or with additional protective materials to avoid initiation of leakage currents and electrical breakdown due to high voltage spikes in equipment. Deterioration of insulations should be considered when selecting materials for insulation and isolation.

A.6 Hostile Threats -T-

A.7 Maneuverability -U-

A.8 Payload Interaction

For power source concepts utilizing nuclear reactors, shield designs should be developed so that the nominal dose to a payload 25 meters from the reactor is -V- neutrons/cm^2 and a gamma dose of -W- Rad. The payload area to be shielded is assumed to have a circular cross-section with a 15 m diameter. It should be clear that these are minimal requirements; scattered (or secondary) radiation from radiators (or other components) extending beyond the volume protected by the shield may pose additional requirements on the radiation shield. These additional requirements are concept specific and must be determined by the designer. Although additional shielding for maintenance may eventually be required, these activities are undefined at this time and shielding requirements for maintenance will not be specified. The effect on the system of varying the nominal dose from -X- neutrons/cm^2 ad a gamma dose of -Y- Rad to -Z- neutrons/cm^2 and -AA- Rad should also be described.

Mass (Grams)	Impact Fluence (Number/m2)
10^{-6}	5
10^{-5}	1
10^{-4}	.25
10^{-3}	.05
10^{-2}	.0038
10^{-1}	.0013
1	.00023

NOTES:

1. Fluence for 10 years in orbit
2. Reference altitude of 600 - 1100 km
3. Reference: D. Kosler, NASA/JSC

Figure A-4. Space Debris Data

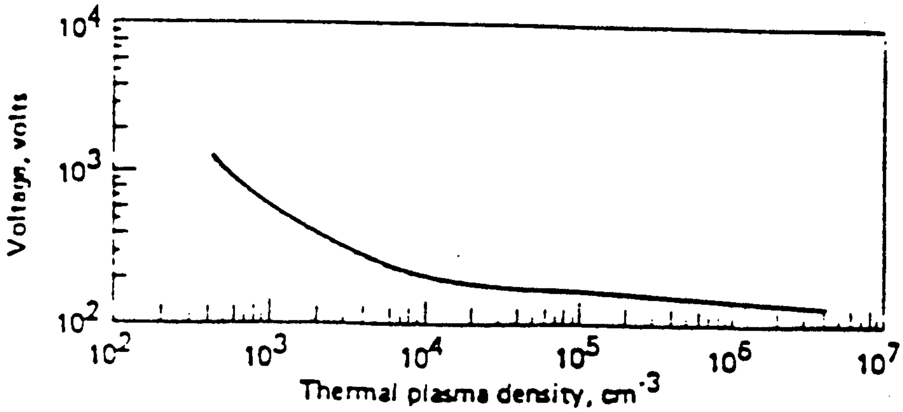

Figure A-5. Voltage Threshold for Breakdown

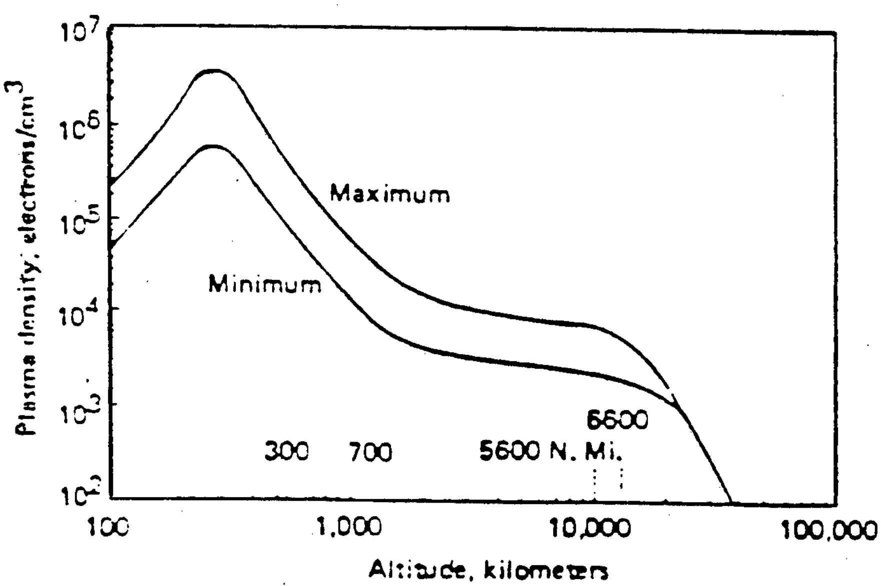

Figure A-6. Plasma Density Versus Altitude

In addition to dose considerations at a nominal separation distance of 25 meters, the effect on system design, operation, and performance of varying this separation distance should also be documented. Payloads and power conditioning systems driven by nuclear power sources may be positioned in close proximity to the reactor or up to a distance of 50 meters away as shown in Figure A-7. (i.e., d_1 and d_2 are independent with a range of 1 to 50 meters).

Thermal radiation on the payload is not to exceed 0.14 watts/cm^2. Electromagnetic interference is to meet MIL-STD-461B. Dynamic isolation of the payload is yet to be determined (TBD).

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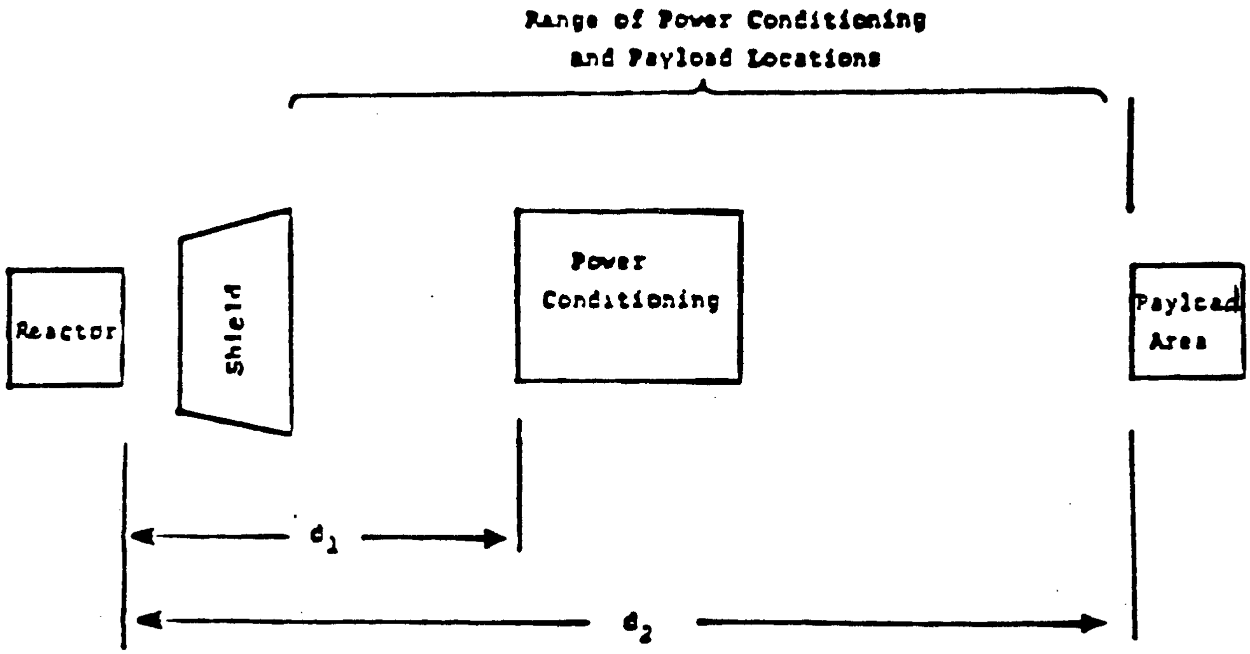

Figure A-7. Power Conditioning System Location

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APPENDIX B

POWER SYSTEM DATA SHEETS

APPENDIX B

POWER SYSTEM DATA SHEETS

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NDR/DISC MHD MMW POWER SYSTEM DATA

B.1 SUMMARY SHEET

Date 01/04/88

Reference

A. Power System Summary

1. Burst Mode System

a. Type	NERVA Derivative Reactor/MHD
b. Fuel	UC-ZrC-C
c. Spectrum or Basic Parameter	Epithermal
d. Coolant	Hydrogen with Cesium Seed
e. Power Conversion	Open Cycle Disk MHD Generator
f. Heat Rejection Mode	Recuperative with Hydrogen Exhaust

2. Secondary Loop	None

B. Assumptions

(Classified Sections May be Submitted in a Separate Document)

1. Max Burst Power - (MW_e)	100
2. Operating Time Burst - (s)	500
3. Burst Energy - (MW_e s or MJ_e)	50,000
4. Other	N/A

C. System Masses - (Metric Tonnes)

Power Source	2.20
MHD Generator	2.14
Magnet	0.72
Energy Storage	0.09
Auxiliary Heat Rejection	0.14
Auxiliary Shielding	0.90
Hydrogen Tank	0.58
Hydrogen Pump	0.39
Misc. Structure & Controls	0.95
Total Dry Mass w/o PCS	8.11
Hydrogen	5.68
Total System Mass w/o PCS	13.79
Power Conditioning System	25.30
Total System Mass	39.09
Total Integrated System Mass*	32.83

*Hydrogen Supplied from Platform

D. Unique Features

1. Inherent independent and diverse decay heat removal paths in reactor
2. Independent magnet energizing/ power source
3. Reverse field energy extraction

B.2 REACTOR AND SHIELD DATA

		Reference
A. Reactor Data		
1. Fuel		
a. Fuel		
	- Composition	UC_2
	- ^{235}U Mass (kg)	
	- Total Fuel Mass (kg)	
	- Enrichment (%)	93.15
	- Density (g/cm^3)	12.8
b. Cladding		
	- Material	ZrC
	- Thickness (mm)	0.05
c. Configuration		Hexagonal - 19 channels
d. Fuel Elements		Composite, UC with ZrC and C, ZrC coated
	- Dimensions Across Flats/Length (cm)	
	- No. of Units	
e. Unfueled Elements		
2. Moderator		
a. Material		Graphite and ZrH
b. Mass (kg)		
c. Mod./Fuel		
d. Configuration		Fuel matrix and support element
3. Axial Reflector		
a. Material		A-286, Be
b. Mass (kg)		
4. Radial Reflector		
a. Material		Be, A-286, ZrC, C
b. Mass (kg)		
5. Active Control		
a. Type		Drums
b. No. Units		12/18
c. Mass (kg)		Included above

B.2 REACTOR AND SHIELD DATA (Continued)

		Reference
6.	Passive Control	
	a. Type	
	b. Mass (kg)	
7.	Core Dimensions	
	a. Diameter (cm)	49
	b. Length (cm)	132
	c. Volume (m^3)	0.26
8.	Reactor Dimensions	
	a. Diameter (cm)	89
	b. Length (cm)	
9.	total Mass	
	a. Core (kg)	
	b. Reactor (kg) w/o PV	
10.	Volume Fractions Core	
	a. Fuel	
	b. Coolant	
	c. Unfueled graphite	
	d. Structure	
	e. ZrC coating	
11.	Parameters	
	a. Max. Fuel Temp. (K)	3050
	b. Max. Clad Temp. (K)	
	c. Avg. Fuel Temp. (K)	
	d. Avg. Prompt Temp. Coef. ($/K)	Negative
	e. Prompt Neutron Generation Time (sec)	
	f. Other Feedback Coef.	
	g. Max n-flux, Thermal (n/cm^2 sec)	
	h. Max n-flux, Total (n/cm^2 sec)	
	i. Max - flux (r/hr)	
	j. Avg. % Burnup (%)	< 1.0
	k. Max. % Burnup (%)	< 1.0
	l. Max. Permitted Specific Power (W/g)	
	m. Avg. Power Density (W/cm^3)	
	n. Specific Core Heat Trans. Area (cm^2/g)	

B.2 REACTOR AND SHIELD DATA (Continued)

	Reference
12. Reactivity Defect	
a. Burnup (%)	Negligible
b. Fission Product ($)	
c. Xe ($)	
d. Temp. Defect (%)	-0.6
e. Other ($)	
13. Water Immersion K_{eff}	0.95
14. Reactivity Control	
a. Active ($)	7.4
b. Passive ($)	
15. Pressure Vessel	
a. Material	
b. Thickness (cm)	1.0
c. Max. Temp., (K)	1200
16. Other Components	
B. Shield Data	
1. Geometry	Within Reactor Vessel
2. Gamma Shield	
a. Material	ZrH
b. Thickness (cm)	
c. Mass (kg)	
3. n-Shield	Included Above
a. Material	
b. Thickness (cm)	
c. Mass (kg)	
4. Transmitted Dose Rate, Max. (at shield surface)	
a. n (n/cm^2)	
b. q (R/hr)	
5. Cooling Requirements	Direct Hydrogen
6. Payload Separation Distance (m)	

B.3 HEAT TRANSPORT

	Reference
A. Burst	
1. Cycle type	Open Cycle MHD Disk
2. No. of loops	1
3. Net efficiency	N/A
4. Net Energy Extraction (MJ/kg)	20
B. Power Source Coolant Data (Reactor)	
1. Burst	
a. Coolant	$H_2 + Cs$
b. Max velocity (m/sec)	
c. Pressure (Atm) (Exit)	17
d. Inlet temp. (°K)	660
e. Outlet temp. (°K)	2900
f. Pressure drop (Atm)	11

B.4 POWER CONVERSION

	Reference
A. Power Conversion Data	
1. Type	Open Cycle Disk MHD
2. Mass (kg)	2858
3. Volume (cm^3)	N/A
4. Materials	Super Alloy, Titanium, Boron Nitride, Carbon-Carbon Composite, Aluminum, Tungsten
5. No. of Units	1
6. Shaft Speed (rpm)	N/A
7. Cooling Method	Regenerative with hydrogen working fluid
8. Coupling Method	N/A
9. Inlet Stagnation Temp (K)	2900
10. Voltage (V)	12,000
11. Current (A)	7000, 10,000, 7000
12. AC/DC	DC
13. No. of Phases	N/A
14. Frequency (Hz)	N/A
15. Specific Power (kW/kg)	38
16. Energy Extraction (MJ/kg)	20
B. Channel	
1. Type	Three Section Disk
2. Dimensions	
Inlet Radius & Height (m)	0.18 x 0.04
Outlet Radius & Height (m)	0.9 x 0.16
3. Mass (kg)	2138
Ti Structure (kg)	1128
BN Insulation (kg)	1010
4. Number of Electrode	4
5. Enthalphy Extraction (MJ/kg)	20
6. Overall (Turbine) Efficiency (PCT)	N/A
7. Inlet Conditions	
Pressure (Atm)	1.0
Temperature (K)	1627
Mach Number	2.4
Velocity (m/s)	7170
Flow Rate (kg/s)	5.47
8. Outlet Conditions	
Pressure (Atm)	0.25
Temperature (K)	1522
Mach Number	1.16
9. Surface Temperature (K)	1300
10. Heat Loss (MWt)	3.6
11. Peak Electrode Current Density (A/cm^2)	N/A
12. Maximum Hall Field (kV/m)	41.2

	Reference
13. Cooling Flow Inlet	
Pressure (Atm)	63.2
Temperature (K)	27
Flow Rate (kg/s)	5.45
14. Cooling Flow Exit	
Pressure (Atm)	36.6
Temperature (K)	650
15. Number of Channels	3 sections
16. MHD Gross Power Before Inversion (MW_e)	108
17. MHD Gross Power After Inversion (MW_e)	101
18. Inverter Efficiency (PCT)	96
19. Lead Losses (PCT)	3

C. Magnet

1. Type	Split Solenoid Pair/Aluminum Conductor
2. Dimensions	
Radius (mean) (m)	0.52
Overall Diameter (m)	1.27
Gap (m)	0.20
Height (m)	0.14
3. Field Strength (Tesla)	
Peak	4.0
Average	3.5
4. Current Density (A/m^2)	5.3×10^7
5. Energy Storage (MJ)	6.0
6. Mass (kg)	720

D. Reactor Exit Plenum and Nozzle

1. Length (m)	0.36
2. Mass (kg)	63
3. Exit Mach Number	2.4
4. Heat Loss (MWt)	2.9

E. Seed Feed and Management

1. Type	Pumped Liquid Cesium
2. Flow, Total (kg/s)	5.47
Cesium Seed (kg/s)	0.018
Hydrogen (kg/s)	5.45
3. Power Requirement (MW_e)	1×10^{-4}
4. Transport Mechanism	Pumped Liquid
5. Flow Control (PCT)	N/A
6. Number of Modules	N/A
7. Key Component	N/A
8. Minimum Useful Life (Years)	N/A
9. Replacement Time (hrs)	N/A

B.5 HEAT REJECTION

	Reference
A. Heat Rejection Data	
1. Type	Auxiliary Cryogenic Cooler
2. Mass (kg)	144
3. Surface Area (m^2)	18
4. Materials	Various
5. Working Fluid	N/A
6. Pump	
a. Type	Heat Pipe
b. Power (MW)	N/A
7. Armor Material	-
8. Inlet Temperature (K)	400
9. Outlet Temperature (K)	400
10. Inlet Press (MPa)	N/A
11. Outlet Press (MPa)	N/A
12. Efficiency	N/A

B.6 ENERGY STORAGE

		Reference
A.	Stored Power	
1.	Type	Battery/Magnet Power Supply
2.	Maximum power, operating power and run time	(175 kW_e, 35 kW_e, 400 s)
3.	Number of identical parallel units, if modularized system	1
4.	Mass of entire storage system (kg)	90
5.	Dimensions of each modular unit or entire storage system (meters) (system elements)	N/A
6.	Storage media (type used)	N/A
7.	Storage temp (K)	N/A
8.	Storage Press (MPa)	N/A
9.	Total mass of storage media (kg)	N/A
10.	Containment subsystem	N/A
11.	Mass of containment subsystem (kg)	N/A
12.	Discharge subsystem	N/A
13.	Mass of discharge subsystem (kg)	N/A
14.	Charging subsystems	N/A
15.	Mass of charging subsystem (kg)	N/A
16.	Storage to prime power system interface	N/A
17.	Mass of interface equipment (kg) (storage system performance)	N/A
18.	Storage system specific energy density (watt-hr/kg)	N/A
19.	Storage system specific discharge power density (kW/kg)	N/A

B.6 ENERGY STORAGE (Continued)

		Reference
20.	Overall turnaround storage efficiency (net energy out/net energy in) (discharge performance)	N/A
21.	Maximum power level during discharge (MW_e)	N/A
22.	Number of seconds sustainable	N/A
23.	Heat rejected by storage system during discharge (MW_t) and rejection temp (K)	N/A
24.	Overall amount of energy storage (MJ)	N/A
25.	Maximum depth of discharge (e.g., maximum kJ delivered/overall amount stored) (recharge performance)	N/A
26.	Recovery time from maximum discharge (sec)	N/A
27.	Input power level during recovery	N/A
28.	Heat rejected by storage system during recovery, (kW_t, or MW_t) and rejection temperature (deg K)	N/A
29.	Output voltage	N/A
30.	Output current	N/A
31.	AC/DC	N/A
32.	Frequency (Hz)	N/A
33.	Critical Statepoints	N/A
34.	Other	N/A

B.7 POWER CONDITIONING

	Reference
1. Power Conditioning (P.C.) Concept	Inverters, Rectifiers, and Transformers
2. Quantity of P.C. Units	~ 20
3. Separate P.C. Units for Steady-State and Burst Modes	1
4. System Weight and Specific Power (kg, kW/kg)	25,300, 0.253
5. Electronics Heat Dissipation Requirements (kW)	4.0
6. Heat Sink Mass and Specific Power (kg, kW/kg)	N/A
7. Cooling	Regenerative/Hydrogen Working Fluid
8. P.C. Semiconductor Technology	GTOs
9. Regulation Scheme	(output voltage control) % Droop at Full Load
10. Regulator Heat Dissipation Requirements (kW)	N/A
11. Power Transmission Conductor Material	Aluminum
12. Conductor/Cable Mass and Mass Per Unit Length (kg, kg/m)	N/A
13. Conductor Heat Dissipation Requirements; Working Fluid (kW)	2.8 - Regenerative Cooling
14. Power Conditioning Radiation Shielding, if Any	--
15. Voltage Output from P.C. (kV)	100
16. Amperage Output from P.C. (A)	1000
17. Output Frequency	DC

APPENDIX C

SHUTTLE ORBITER/CARGO BAY INTERFACE DATA

APPENDIX C

SHUTTLE ORBITER/CARGO BAY INTERFACE DATA

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APPENDIX C SHUTTLE ORBITER/CARGO BAY INTERFACE DATA

C.1 INTRODUCTION

This appendix includes excerpts from NASA Document JSC 07700 Volume XIV (ICD 2-19001) "Shuttle Orbiter/Cargo Standard Interfaces" that are relevant to the design and development of the space-based multimegawatt MHD power system. Consideration of these interface factors can influence the selection of the conceptual design, location of components, materials, dimensions, weights and methods of mounting equipment so as to survive launch, on-orbit operation, return to Earth in the event of a launch abort, and return to Earth for any reason.

C.2 GENERAL CRITERIA

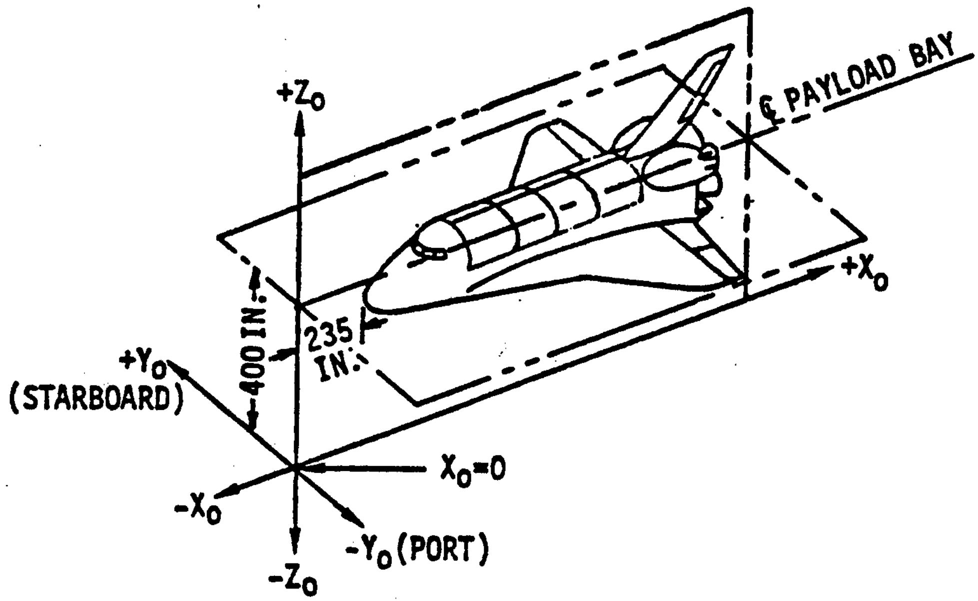
Payloads are constrained to the dimensional envelope beginning with payload installation and ending with payload deployment or removal. Payloads are subject to the induced environment and are constrained to the cargo thermal and dynamic envelope during the complete flight beginning with the installation.

In selection of design concepts and materials, consideration must be given to effects of the launch and the de-orbit return on the MHD power system. Components must be mounted and supported so as to survive a launch and de-orbit return to Earth without compromising the integrity of the equipment, the safety of the crew or the STS vehicle, or the safety of the Earth environment.

C.2.1 Coordinate System

The coordinate systems to be used when analyzing the effects of the shuttle on the design of the MHD power system are shown in the following:

Figure C-1. Orbiter Coordinate System
Figure C-2. Payload Coordinate System
Figure C-3. Orbiter Dynamical Body Axes Coordinate System



Origin: In the Orbiter plane of symmetry, 400 inches below the center line of the payload bay and at Orbiter X station=0.

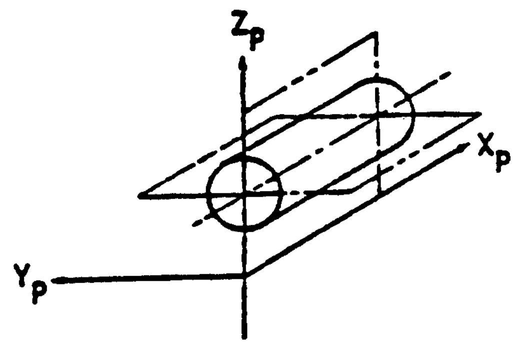
Orientation: The X_O axis is in the vehicle plane of symmetry, parallel to and 400 inches below the payload bay centerline. Positive sense is from the nose of the vehicle toward the tail.

The Z_O Axis is in the vehicle plane of symmetry, perpendicular to the X_O axis positive upward in landing attitude.

The Y_O axis completes a right-handed system.

Characteristics: Rotating right-handed cartesian.
The standard subscript is O (e.g., X_O).

Figure C-1. Orbiter Coordinate System



TYPE: ROTATING, PAYLOAD REFERENCED

ORIGIN: 200 INCHES BELOW THE CENTERLINE OF THE FORWARD END OF THE PAYLOAD

ORIENTATION AND LABELING:

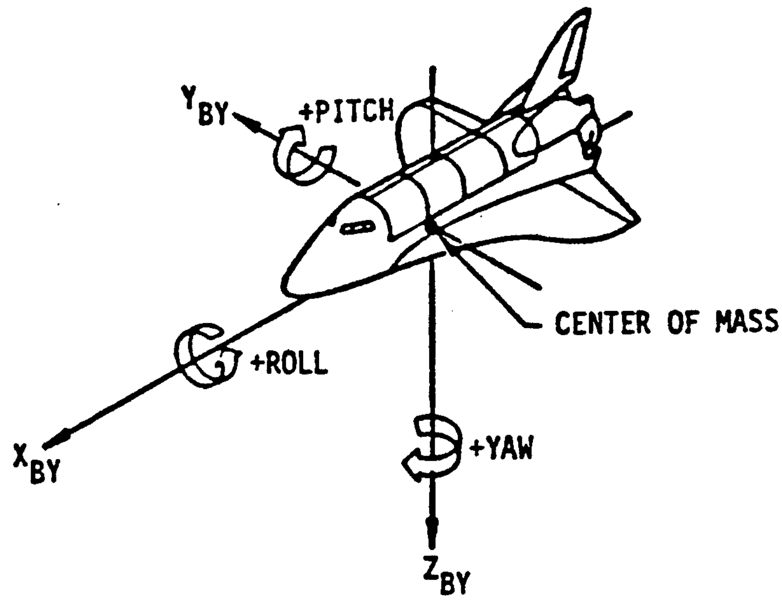
X AXIS IS NEGATIVE IN THE DIRECTION OF LAUNCH, PARALLEL TO THE ORBITER PAYLOAD BAY CENTERLINE

Z AXIS IS POSITIVE UPWARD IN THE ORBITER LANDED POSITION, PARALLEL TO ORBITER Z AXIS

Y AXIS COMPLETES THE RIGHT-HANDED SYSTEM

THE STANDARD SUBSCRIPT IS P

Figure C-2. Payload Coordinate System



NAME:	BODY AXIS COORDINATE SYSTEM
ORIGIN:	CENTER OF MASS
ORIENTATION:	X_{BY} AXIS IS PARALLEL TO THE ORBITER STRUCTURAL BODY X_o AXIS: POSITIVE TOWARD THE NOSE
	Z_{BY} AXIS IS PARALLEL TO THE ORBITER PLANE OF SYMMETRY AND IS PERPENDICULAR TO X_{BY}, POSITIVE DOWN WITH RESPECT TO THE ORBITER FUSELAGE
	Y_{BY} AXIS COMPLETES THE RIGHT-HANDED ORTHOGONAL SYSTEM
CHARACTERISTICS:	ROTATING, RIGHT-HANDED, CARTESIAN SYSTEM THE STANDARD SUBSCRIPT IS BY (E.G., X_{BY})

Figure C-3. Orbiter Dynamical Body Axes Coordinate System

C.2.2 Acceleration Levels

Figure C-4 defines the maximum acceleration levels for the thrusting portion of a launch.

C.2.3 Physical Interfaces

Figure C-5 defines the field of view angular clearances of the Shuttle Cargo Bay for use in selecting a conceptual design that can fit into the Cargo Bay and be removed from there.

Figure C-6 defines the physical interface locations dimensions of the Shuttle Orbiter Cargo Bay for installation of the MHD power system during a launch.

Figure C-7 defines the allowable payload stiffness for installation of the MHD power system.

C.3 Payload Bay

C.3.1 Orbiter/Payload Structural Attachments

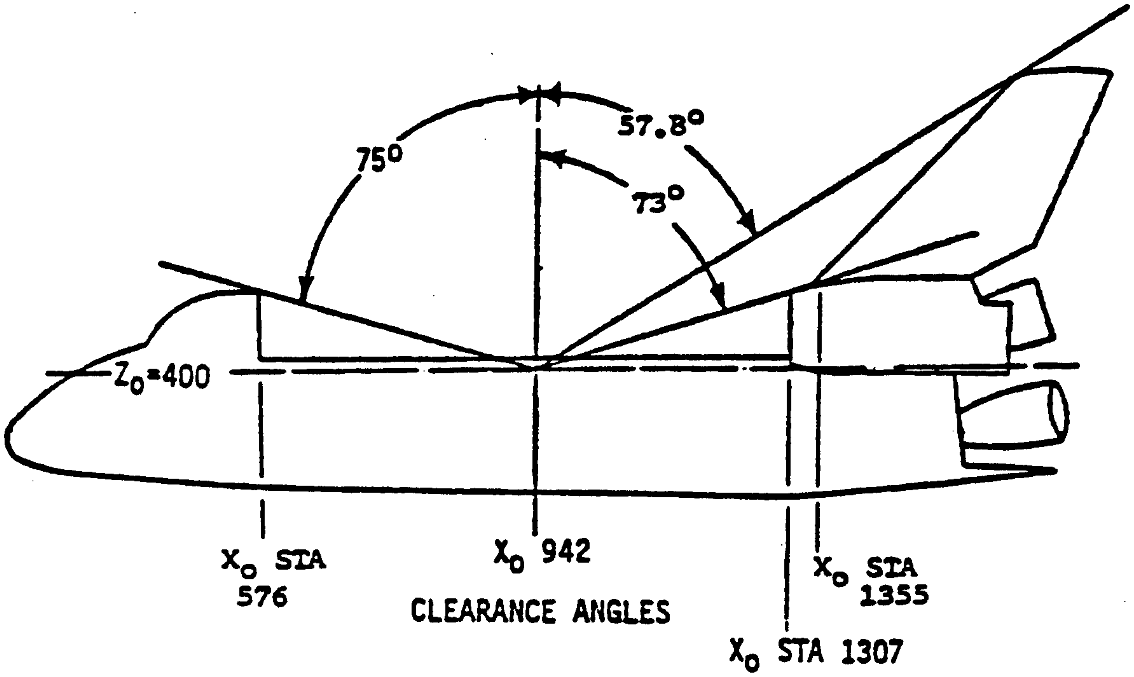
Payloads/Payload carriers shall be supported in the Cargo Bay on payload trunnions extending beyond the payload envelope in the $\pm Y_0$ directions at $Z_0 = 414$ and in the minus Z_0 direction at $Y_0 = 0$. The trunnions shall be free to slide axially through split self-aligning bearings contained in Orbiter attach fittings defined below, which, in turn, shall be supported on bridges at the sides of the Cargo Bay (longerons) and the bottom of the Cargo Bay (keel). The bridges shall distribute the loads to the Orbiter structure. The trunnion/bearing surfaces shall be the interfaces which transmit loads between the Orbiter and the Payload.

The design concept for payload retention at the longeron shall permit Stabilizing Fittings to carry only Z-Z loads by sliding fore and aft on the

DIRECTION	TRANSLATIONAL ACCELERATION FT/SEC² (MPS²)					ROTATIONAL ACCELERATION DEG/SEC²			
RCS SYSTEM	+ x	− x	± y	+ z	− z	± ROLL	+ PITCH	− PITCH	± YAW
PRIMARY THRUSTER	0.6 (0.18)	0.5 (0.16)	C.7 (0.22)	1.3 (0.40)	1.1 (0.34)	1.2	1.4	1.5	0.8
VERNIER THRUSTER	0 0	C 0	0.007 (0.0021)	0 0	0.008 (0.0024)	0.04	0.03	0.02	0.02

- Based on mass properties from JSC C8934 Shuttle Operational Data Book, Volume II, Mission Mass Properties for Orbiter at pre-deorbit with 32 K lb (14515 kg) cargo
- Coordinate system directions are the same as those shown in Figure C-1.

Figure C-4. Typical Orbiter RCS Maximum Acceleration Levels



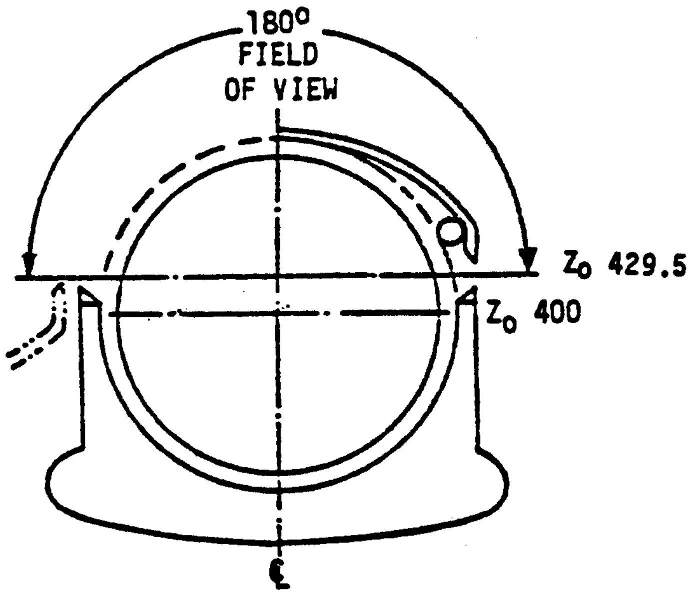


Figure C-5. Cargo Bay Field of View

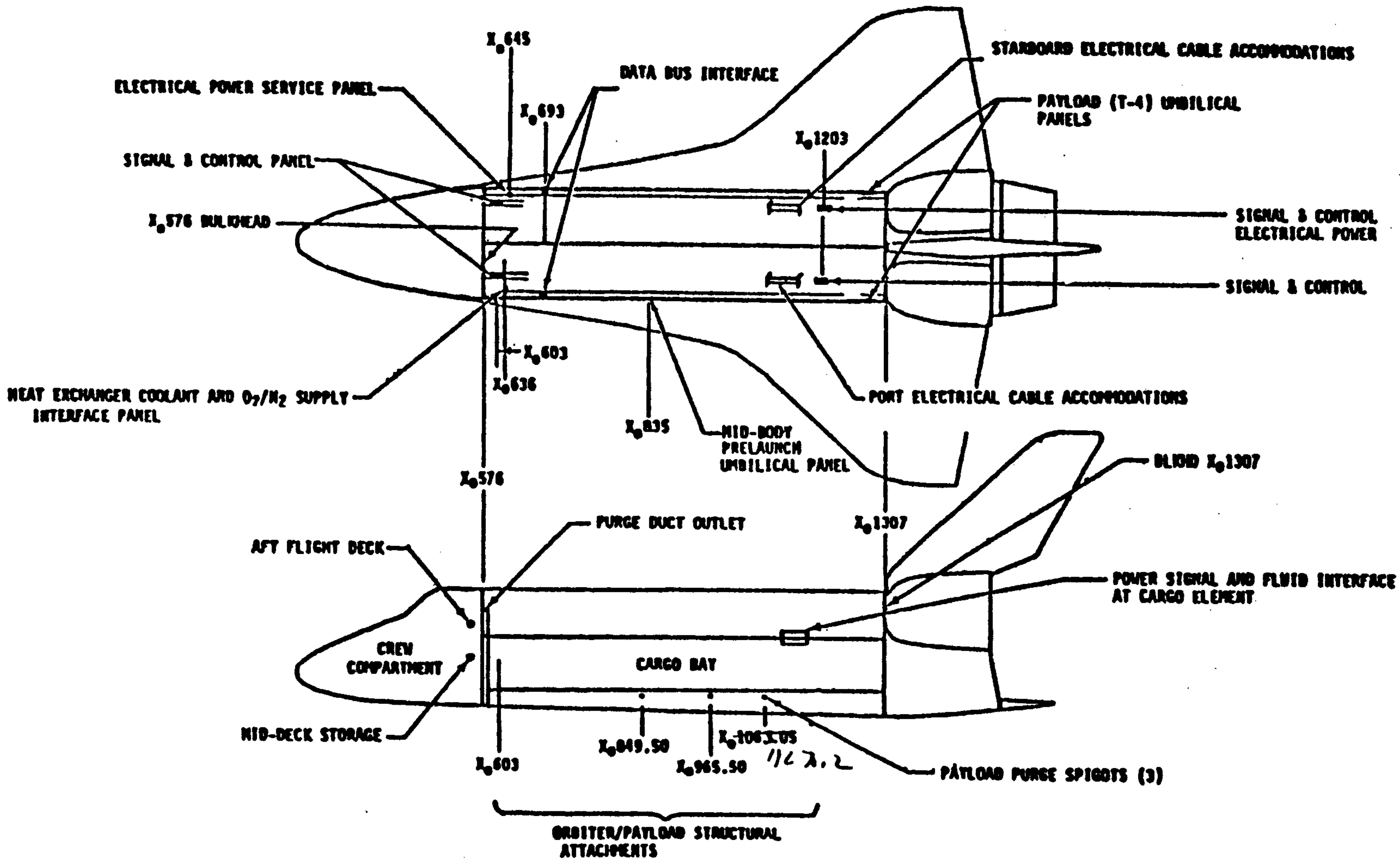


Figure C-6. Shuttle Orbiter Payload Physical Interface Locations

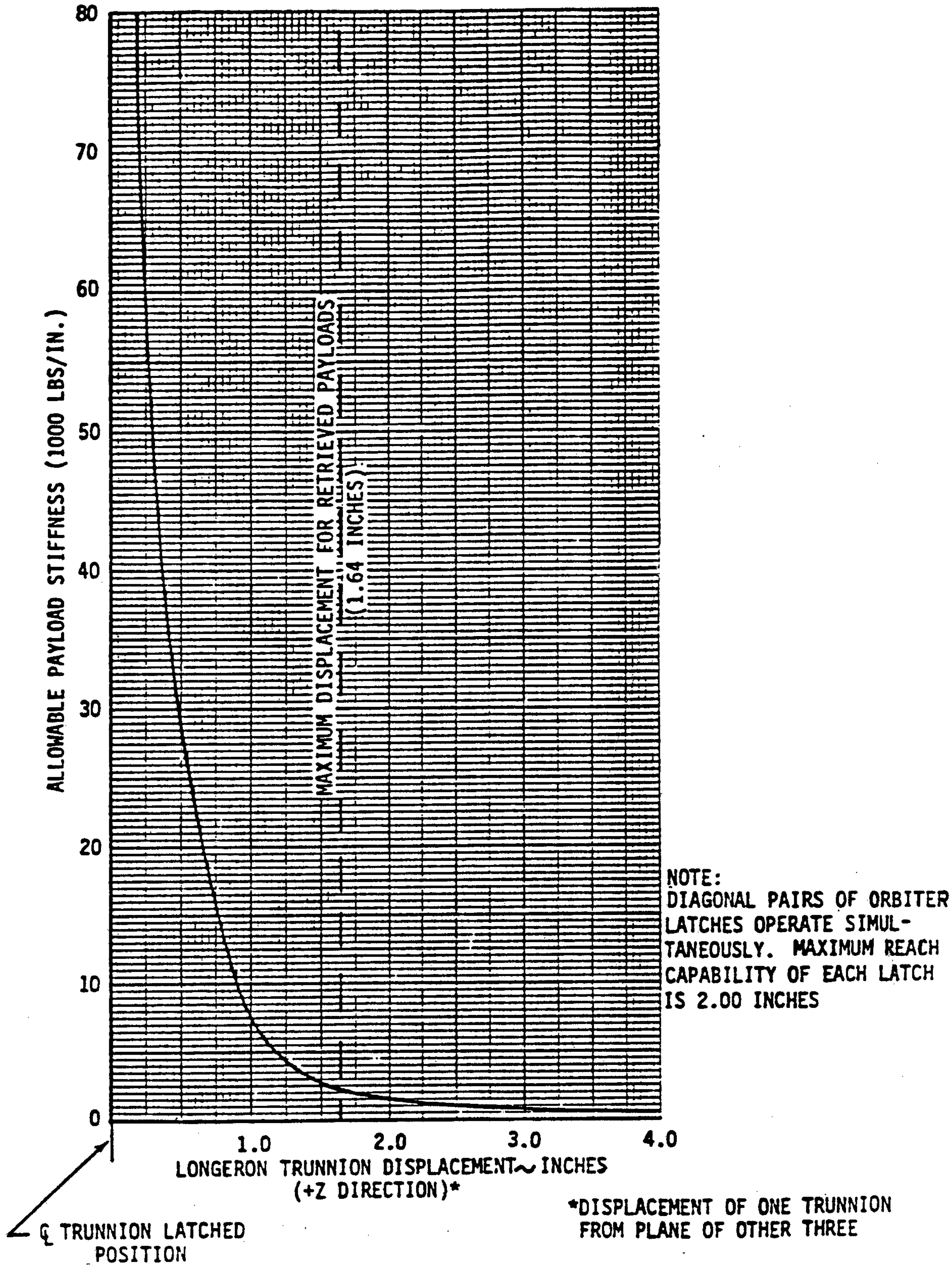


Figure C-7. Allowable Payload Stiffness Based on Orbiter Latching Capability longeron bridge cap relieving X-X loads, while the payload trunnion is free to slide through the bearing relieving Y-Y loads. Insertion of shear pins between longeron retention fitting and the bridge converts it to a Primary Fitting, which shall carry only X-X loads in addition to Z-Z loads. The keel fitting shall carry only Y-Y loads from the payload keel trunnion which is free to slide in the bearing relieving Z-Z loads; the fitting is free to slide on the keel bridge in the X_o direction, thus relieving X-X loads (Auxiliary Fitting) or can be pinned to the keel bridge to carry X-X loads. Only the payload attachment fittings required for a particular flight will be installed.

C.3.2 Attach Fitting for Deployable Payloads

The mechanism for deployment and retrieval of payloads shall contain an alignment guide and a payload trunnion latch to secure the payload; the trunnion latch shall be operated by an electromechanical actuator. The mechanism shall be capable of deploying and retrieving statically determinate or indeterminate payloads.

C.4 Cargo Bay Structural Interfaces

C.4.1 Interface Force Constraints

Interface forces shall be constrained to the Orbiter attach point limit-load capability.

C.4.1.1 Friction-Induced Loads

Design of the Orbiter and payloads shall include the effects of friction induced loads at both longeron and keel interfaces.

C.4.2 Attachment Mechanism Deflection Limits

With the exceptions of attachment mechanisms and umbilicals, the cargo in the Cargo Bay shall remain at all times within the payload thermal and dynamic envelope. The spherical bearings in the longeron and keel attach fittings provide for misalignment and for relative rotational deflection between the payload trunnion and the Orbiter structure. The available alignment cone angles constitute the limits on the relative rotational deflections between the payload trunnions and the Orbiter structure. These limits are apportioned to the payload and to the Orbiter in Figure C-8 for use in preliminary payload design. The total relative deflection limits for the final payload design shall be verified by coupled dynamic and quasi-static analyses.

C.4.3 Cargo Limit-load Factors/Angular Accelerations

The load factors/angular accelerations specified in Figures C-9, C-10, C-11, and C-12 shall be used for preliminary design of cargo and carrier primary structure and for determination of preliminary Orbiter/cargo interface loads as the guiding criteria only. The center of rotation for angular accelerations is at the cargo element center of gravity. The load factors/angular accelerations for emergency landing conditions are defined in Paragraph C.4.3.3.

Cargo load factor/angular acceleration is defined as the total externally applied force/moment on the cargo or cargo component divided by the corresponding total or component weight/masss moment of inertia and carries the sign of the externally applied force/moment in accordance with the Orbiter coordinate system. (See Figure C-13).

These load factors/angular accelerations are valid for any location in the bay. The load factors/angular accelerations result from the response of the Shuttle vehicle structure, including cargo, to external forces corresponding to both quasi-static and transient flight events. These external forces are generated by the thrust, aerodynamics, wind shear, prelaunch restraints, entry maneuvers, landing gears impact, etc.

Accelerations at specific points within the cargo will depend upon cargo design characteristics and mounting methods. Portions of the cargo that are

Interface Location	Rotational Deflection Limits Degrees		
	Payload*	Orbiter*	Total**
Deployable Longeron Fitting	3.0	3.0	6.0
Non-Deployable Longeron Fitting	5.0	3.0	8.0
Active and Passive Keel Fitting	3.0	3.0	6.0

* For preliminary design use only.
** Total relative rotational deflection.

Figure C-8. Payload/Orbiter Rotational Deflection Limits for Preliminary Design

FLIGHT EVENT	LOAD FACTOR g			ANGULAR ACCELERATION RAD/SEC²			CARGO WEIGHT
	Nx	Ny	Nz	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	
ASCENT							
HIGH-Q BOOST ENVELOPE	-1.9	±0.40	0.25 -0.50	±0.10	±0.15	±0.15	Up to 65 Klb
INTEGRATED VEHICLE BOOST MAX Nx	-2.9 -2.6	±0.06 ±0.02	-0.15 -0.20	±0.20 ±0.20	±0.25 ±0.25	±0.25 ±0.25	
ORBITER BOOST MAX Nx	-3.17 -3.05	0 0	-0.60 -0.80	±0.20 ±0.20	±0.25 ±0.25	±0.25 ±0.25	
POST SRB STAGING	-1.10	±0.12	-0.59				
DESCENT							
TAEM: PITCH MANEUVER	1.01 -0.15	0	2.50	0	0	0	Up to 32 Klb
	0.25	0	2.50	0	-0.11	0	
	0.97 0	0	-1.00	0	0	0	
TAEM: ROLL MANEUVER	0.65	±0.12	1.98	±1.28	0.02	±0.13	
TAEM: YAW MANEUVER	0.60 0.56 0.61	±0.85 ±0.49 ±0.002	1.0 1.44 0.92	0 0 0	0 0 0	0 ±0.044 ±0.056	

Figure C-9. Cargo Limit-Load Factors/Angular Accelerations for Preliminary Design (Quasi-Static Flight Events)

FLIGHT EVENT	LOAD FACTOR g			ACCELERATION RAD/SEC²			CARGO WEIGHT
	Nx	Ny	Nz	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	
<u>ASCENT</u>							
LIFT-OFF	-0.2 -3.2	±1.4	2.5 -2.5	±3.7	±7.7	±3.1	Up to 65 Klb (29484 kg)
<u>DESCENT</u>							
LANDING	1.8 -2.0	±1.5	+4.2 -1.0	±4.0	±11.3	±4.9	Up to 32 Klb (14515 kg)

Figure C-10. Cargo Limit-Load Factors/Angular Accelerations for Preliminary Design (Transient Flight Events)

FLIGHT EVENT	LOAD FACTOR g			ACCELERATION RAD/SEC²			CARGO WEIGHT
	Nx	Ny	Nz	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	
DESCENT							
TAEM: Pitch Manuever	1.01 / -0.15	0	2.50	0	0	0	Up to 32 Klb
	0.25	0	2.50	0	-0.11	0	
	0.97 / 0	0	-1.00	0	0	0	
TAEM: Roll Maneuver	0.65	±0.12	1.98	±1.28	0.02	±0.13	
TAEM: Yaw Maneuver	0.60	±0.85	1.0	0	0	0	
	0.56	±0.49	1.44	0	0	±0.044	
	0.61	±0.002	0.92	0	0	±0.056	
TAEM: Pitch Manuever	0.83 / -0.21	0	2.07	0	0	0	65 Klb
	0.21	0	2.07	0	-0.09	0	
	0.81 / 0	0	-0.83	0	0	0	
TAEM: Roll Maneuver	0.54	±0.10	1.65	±1.06	0.02	±0.11	
TAEM: Yaw Maneuver	0.51	±0.75	1.0	0	0	0	
	0.44	±0.45	1.53	0	0	±0.039	
	0.51	±0.012	0.93	0	0	±0.054	

Note: Load factors for non-returnable cargoes between 32,000 lb and 65,000 lb are found by linear interpolation between values given in the table.

Figure C-11. Cargo Limit/Load Factors/Angular Accelerations for Preliminary Design (Descent of Non-Returnable Cargo)

FLIGHT EVENT	LOAD FACTOR g			ACCELERATION RAD/SEC^2			CARGO WEIGHT
	Nx	Ny	Nz	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	
<u>LANDING</u>	1.50 -1.70	±0.80	3.00 -0.20	±4.8	±5.4	±3.0	All Weights

Figure C-12. Cargo Limit/Load Factors/Angular Accelerations for Preliminary Design (Landing of Non-Returnable Cargo)

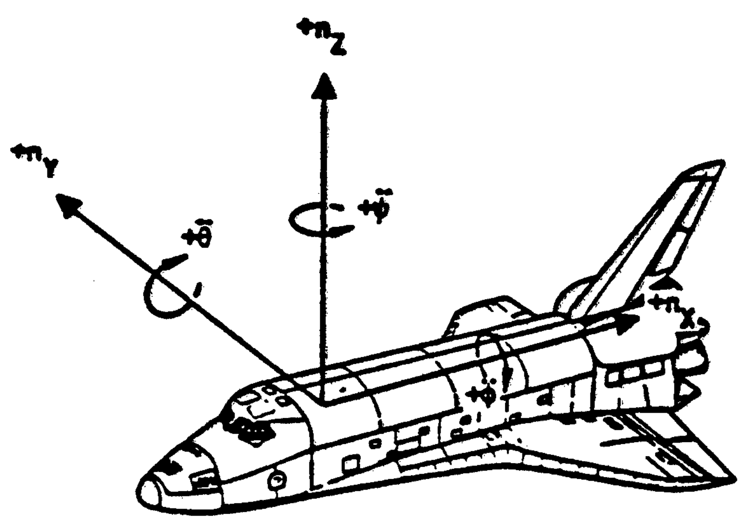


Figure C-13. Sign Convention for Cargo Limit-Load Factors/Angular Accelerations cantilevered from their support points, or that have substantial internal flexibility, may experience higher accelerations than those reflected in the tables.

The load factors/angular accelerations shall be considered in all combinations for each event.

C.4.3.1 Transient Flight Events

The transient flight events correspond to conditions for which the external forces are highly transient in nature and significant elastic response occurs. Shuttle lift-off and landing are events of this type. The associated cargo responses depend on the cargo geometry, stiffness, and mass characteristics. Consequently, design values of cargo/Shuttle interface forces and cargo design loads shall be determined by coupled dynamic analysis. Shuttle dynamic model and forcing functions used for the dynamic analysis shall be included in the cargo element-unique ICD. Typical load factors for the transient events are given in Figure C-10.

The load conditions in Figure C-10 are for an ascent cargo weight of up to a maximum of 65,000 lb (20,484 kg) lift-off cargo and up to a maximum of 32,000 lb (14,515 kg) landing cargo. The maximum symmetric design landing sink speed is 9.6 fps (2.93 mps).

C.4.3.2 Descent and Landing Loads on Non-Returnable Cargoes

Normally non-returnable cargoes, which are required to descend and land with an Orbiter, may use a reduced decent and landing load criterion. This reduced criterion is based upon the low probability of occurrence of the Orbiter having to descend and land with a non-returnable cargo. Figure C-11 provides limit-load factors/angular accelerations for descent of non-returnable cargoes up to 65,000 lb (29,848 kg). Figure C-12 provides limit-load factors/angular accelerations for landing of these non-returnable cargoes.

The landing load factors in both tables correspond to a symmetric landing sink speed of 6.0 fps.

These load factors should be used for preliminary design and should be superseded by dynamic analysis results when available.

Payloads planned for recurring return, including empty cradles, are required to meet the landing load factors of Figures C-9 and C-10 based on 9.6 fps sink rate.

C.4.3.3 Emergency Landing Load Factors

The Orbiter Vehicle design considers safe crew egress following emergency landing or water ditching. Hence, the mounting structures for equipment and crew provisions vessels, and for the payload attachments, shall be designed to load factors equal to or greater than those shown in Figure C-14. The attachment structures (including fittings and fasteners) of the payloads must be designed for emergency landing loads. The attachment structure of payload equipment where failures could result in injury to personnel or prevent egress from the emergency landed vehicle must be designed for this requirement. Payload equipment design shall consider provisions to maximize the probability of safe crew egress following an emergency landing.

C.4.3.4 Factors of Safety for Structural Design

The structural design of all mounting hardware and/or bracketry (or any other structure which could be affected by flight loads) shall assure an ultimate factor of safety $\geq$ 1.4. Pressurized lines and fittings less than 1.5 in. in diameter shall have an ultimate factor of safety $\geq$ 4.0. Those larger than 1.5 in. in diameter shall have an ultimate factor of safety $\geq$ 1.5.

	Load Factor 65 Klb (29484 kg) Up 32 Klb (14515 kg) Down			Load Factor 65 Klb (29484 kg) Down		
CONDITION	X	Y	Z	X	Y	Z
Emergency Landing (Outside Crew Compartment)	+4.5 -1.5	+1.50 -1.50	+4.5 -2.0	+4.50 -0.738	+0.738 -0.738	+2.215 -0.985
Emergency Landing (Inside Crew Compartment)	+20.0 -3.3	+3.3 -3.3	+10.0 -4.4			

Sign convention follows that of the Orbiter coordinate system in Figure C-9.

Emergency landing load factors are ultimate. The longitudinal load factors are directed in all aftward azimuths within a cone of 20 degrees half-angle. The specified load factors shall operate separately.

For cargo weight between 32 klb and 65 klb, use a linear interpolation between the load factors given.

Figure C-14. Emergency Landing Design Load Factors

C.4.3.5 Fracture Control

Structural components, including all pressure vessels, the failure of which could cause destruction of the Orbiter or injury to the crew, shall be analyzed to preclude failures caused by propagation of pre-existing flaws.

C.4.4 Mass Properties Characteristics of Total Cargo

C.4.4.1 Center of Gravity (C.G.) Envelopes Provided by Shuttle Vehicle

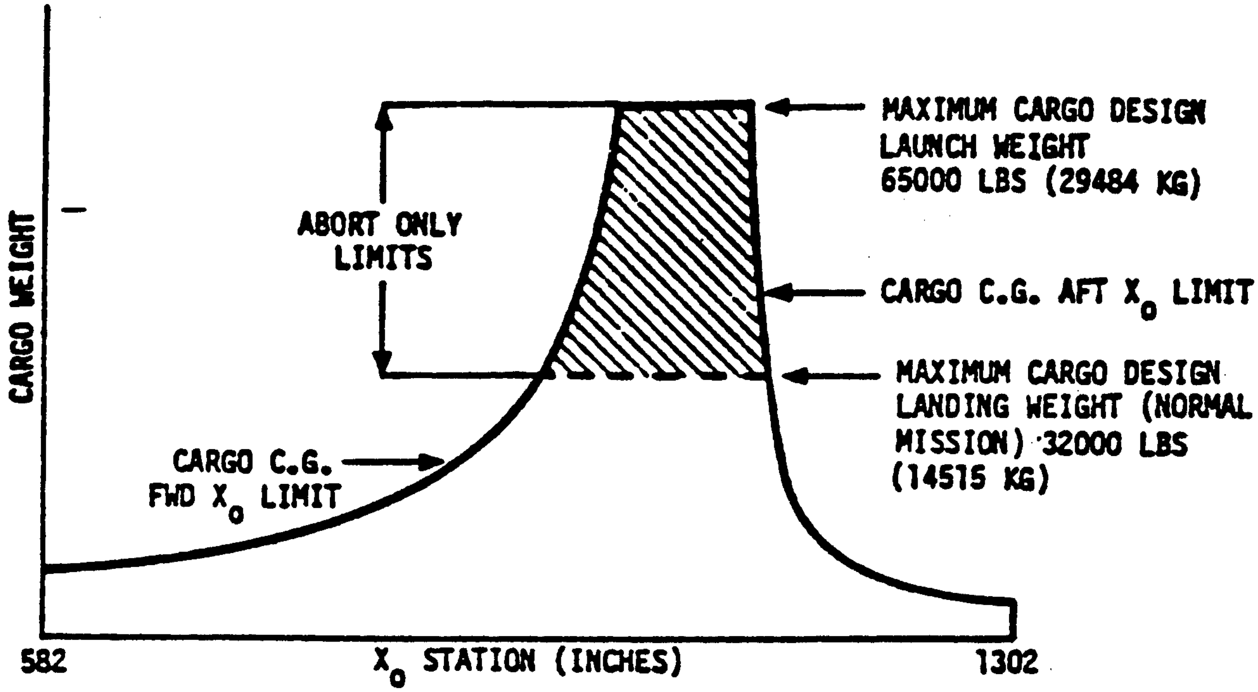
Except for the flight segments indicated below, the Shuttle Vehicle shall perform satisfactorily with no constraints placed upon the Cargo C.G. For these exceptions, Cargo C.G. limit envelopes are defined for each axis by the following:

a. X-axis: Cargo C.G. limits shall be calculated using the equations defined in Figure C-15

b. Y-axis: Cargo C.G. limits shall be calculated using the equations defined in Figure C-16

c. Z-axis: Total Cargo C.G. limits shall be calculated using the equations defined in Figure C-17. C.G. limits for Cargo items mounted on the cargo bay attachments shall be as shown in Figure C-17. In addition to these Cargo Z_o C.G. limits, the Z_o C.G. limits for the summation of all cargo elements mounted on attachment fittings in the cargo bay are defined by the curve ABCDEFGHIJ in Figure C-17.

All items chargeable to Cargo, regardless of location, (e.g., within cargo bay, below cargo bay, in cabin, etc.) shall be included in the calculation to determine the location of the Cargo C.G. The C.G.s shall be constrained within the three-limit envelopes defined above during the following flight segments:



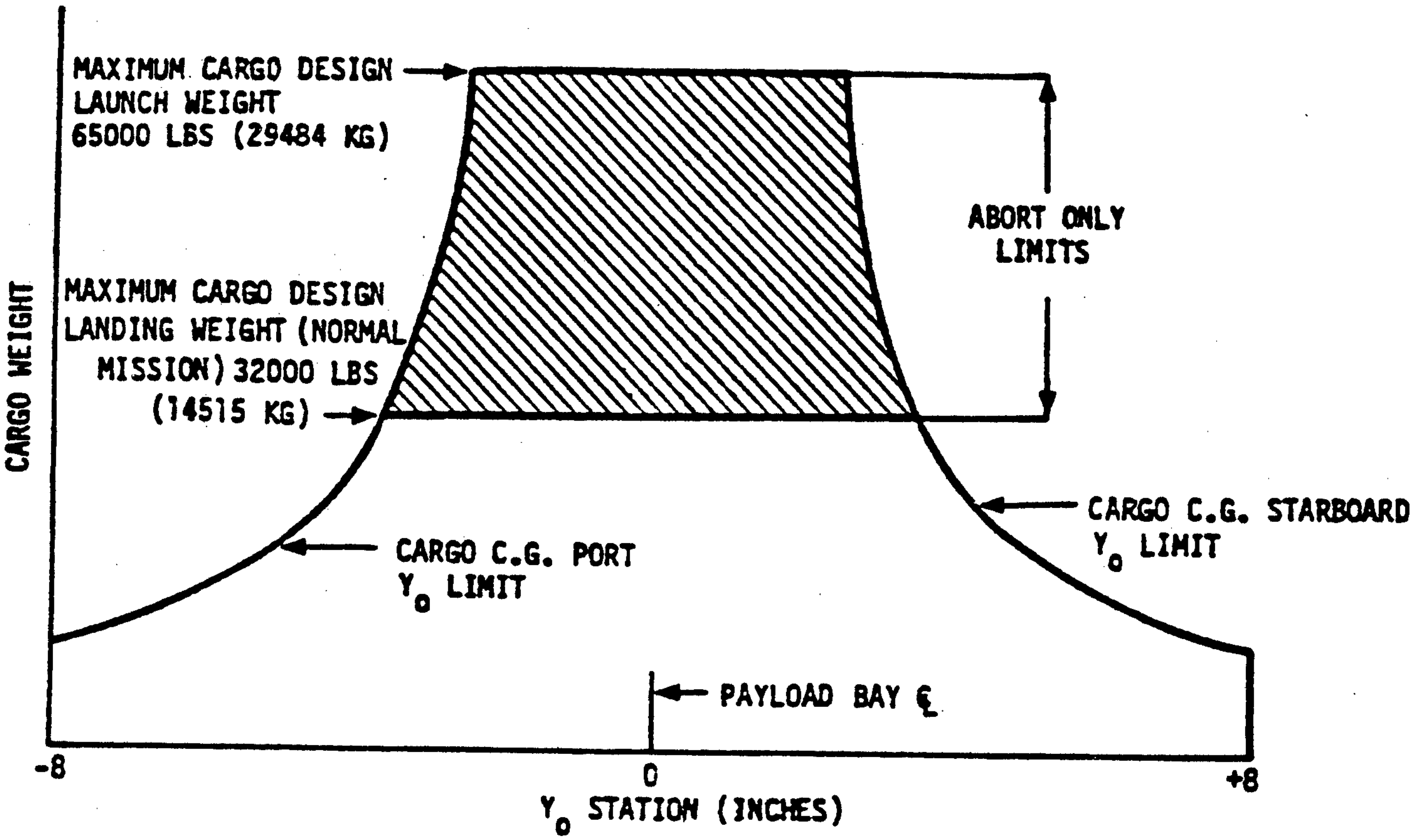
EQUATIONS FOR CALCULATING CARGO X_o (STATION) C.G. LIMITS

$$\text{FWD LIMIT} = \frac{1076.7\ W_c - 3.70 \times 10^6}{W_c}$$

$$\text{AFT LIMIT} = \frac{1108.95\ W_c + 3.4 \times 10^5}{W_c}$$

WHERE W_c = CARGO WEIGHT IN LBS

Figure C-15. Allowable Cargo C.G. Limits (Along X-Axis)

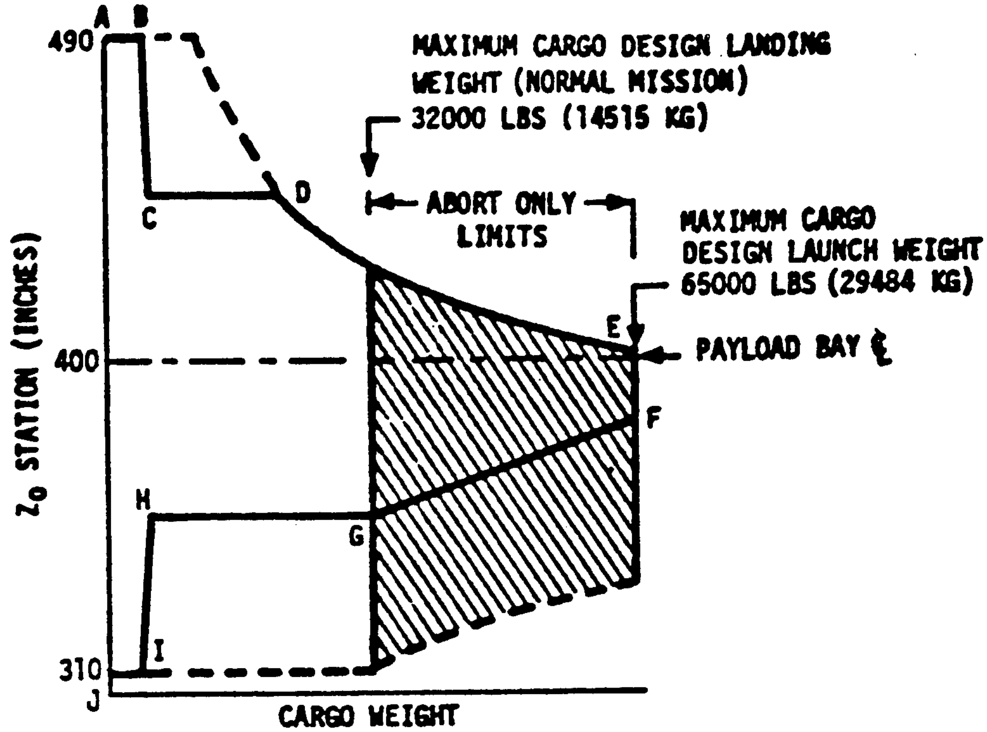


EQUATIONS FOR CALCULATING CARGO Y_o (STATION) C.G. LIMITS

$$\text{LIMIT} = \pm\left[\frac{1.5\ W_c + 6.265\times10^4}{W_c}\right]$$

WHERE W_c = CARGO WT IN LBS

Figure C-16. Allowable Cargo C.G. Limits (Along Y-Axis)



EQUATIONS FOR CALCULATING CARGO Z_0 (STATION) C.G. LIMITS

$$\text{UPPER LIMIT} = \frac{384.5\ W_c + 1.331\times10^6}{W_c}$$

$$\text{LOWER LIMIT} = \frac{360\ W_c - 1.566\times10^6}{W_c}$$

WHERE W_c =CARGO WT IN LBS

PARTIAL PAYLOAD Z_0 (STATION) C.G. LIMITS FOR SUMMATION OF ALL PAYLOADS MOUNTED ON ATTACHMENT FITTINGS IN PAYLOAD BAY (Z_0 C.G. TO REMAIN WITHIN CURVE ABCDEFGHIJ, THE SEGMENTS OF WHICH ARE DEFINED BELOW)

IJAB: SAME AS CARGO C.G. LIMITS ABOVE FOR P/L WT UP TO 4000 LBS

BC: STRAIGHT LINE FROM POINT B (4000 LBS, STA 490) TO POINT C (6000 LBS, STA 445)

CD: STRAIGHT LINE AT STA 445 FROM POINT C (6000 LBS) AND POINT D ON CARGO C.G. LIMITS ABOVE

DEF: SAME AS CARGO C.G. LIMITS ABOVE FROM POINT D (STA 445) TO POINT F (STA 380)

FG: STRAIGHT LINE FROM POINT F(65,000 LBS, STA 380) TO POINT G (32,000 LBS, STA 355)

GH: STRAIGHT LINE AT STA 355 FROM POINT G (32,000) TO POINT H (6000 LBS)

HI: STRAIGHT LINE FROM POINT H(6000 LBS, STA 355) TO POINT I(4000 LBS, STA 310)

Figure C-17. Allowable Cargo C.G. Limits (Along Z-Axis)

a. Normal entry through landing.

b. MFCO through landing for RTLS abort.

c. Entry through landing for all other intact abort modes. (Refer to TBD.)

During an abort, if the Cargo C.G. is not within the entry and landing design limits, the Orbiter (with Cargo included) must provide the means to attain an in-limits C.G. location prior to: (1) ET separation, for an RTLS abort, or (2) entry and landing for an on-orbit abort.

C.4.5 Acoustics

The acoustic levels in an empty cargo bay that are defined in Figure C-18 represent the minimum level to which a payload must be certified to be considered safe to fly on the STS.

The acoustic levels during orbit, entry and landing are significantly below the ascent levels and shall be assumed negligible.

Acoustic levels for specific payloads are dependent on payload geometry, surface area and acoustic absorption characteristics and will differ from those of the empty cargo bay.

C.4.6 Random Vibration

The random vibration environments associated with STS lift-off are specified for both trunnion mounted payloads and for longeron/adapter mounted payloads. Environments may be considered statistically uncorrelated.

C.4.6.1 Random Vibration for Trunnion Mounted Payloads

The random vibration environments for the longeron trunnion and keel trunnion interfaces are specified in Figures C-19 and C-20. The criteria are specified

1/3 Octave Band Center Frequency (Hz)	Sound Pressure Level (dB) ref. 2X10⁻⁵ N/m²	
	Lift-off	Aeronoise
	5 Seconds/Flight*	10 Seconds/Flight*
31.5	122.0	112.0
40.0	124.0	114.0
50.0	125.5	116.0
63.0	127.0	118.0
80.0	128.0	120.0
100.0	128.5	121.0
125.0	129.0	122.5
160.0	129.0	123.5
200.0	128.5	124.5
250.0	127.0	125.0**
315.0	126.0	125.0**
400.0	125.0	124.0**
500.0	123.0	121.5
630.0	121.5	119.5
800.0	120.0	117.5
1000.0	117.5	116.0
1250.0	116.0	114.0
1600.0	114.0	112.5
2000.0	112.0	110.5
2500.0	110.0	108.5
Overall	138.0	133.5

* Time per flight does not include a scatter factor.

** NOTE: Narrow band discrete noise is radiated from the cargo bay vent doors during transonic/low supersonic flight. The noise radiated from any one vent is described below:

This environment is not intended for full payload exposure but only to those areas of the payload adjacent to a cargo bay vent opening.

One-third Octave Band Center Frequencies, Hz	Sound Power Level dB re 10^{-12} watts
	8 Seconds/Flight
250	128
315	136
400	130

Figure C-18. Orbiter/Cargo Bay Internal Acoustic Environment

Payload Weight *Less Than 10,000 Lbs.		
o X Axis	20 to 50 Hz 50 to 125 Hz 125 to 300 Hz 300 to 2000 Hz Overall = 3.0 g(rms)	.0015 G²/Hz +9 dB/oct .025 G²/Hz -9 dB/oct
o Y Axis (Fwd of Sta. Xo = 919)	20 to 68 Hz 68 to 100 Hz 100 to 380 Hz 380 to 2000 Hz Overall = 2.5 g(rms)	.004 G²/Hz +9 dB/oct .013 G²/Hz -9 dB/oct
o Y Axis (Aft of Sta. Xo = 919) And o Z Axis	20 to 68 Hz 68 to 125 Hz 125 to 300 Hz 300 to 2000 Hz Overall = 3.0 g(rms)	.004 G²/Hz +9 dB/oct .025 G²/Hz -9 dB/oct
Payload Weight *Greater Than 10,000 Lbs.		
o X Axis	20 to 50 Hz 50 to 80 Hz 80 to 480 Hz 480 to 2000 Hz Overall = 2.0 g(rms)	.0015 G²/Hz +9 dB/oct .0063 G²/Hz -9 dB/oct
o Y and Z Axes	20 to 68 Hz 68 to 80 Hz 80 to 480 Hz 480 to 2000 Hz Overall = 2.4 g(rms)	.004 G²/Hz +9 dB/oct .0063 G²/Hz -9 dB/oct

The associated time duration is 20 seconds per axis per flight which includes a fatigue scatter factor of 4.

*Total payload weight is irrespective of the number of mounting points.

Figure C-19. Orbiter/Cargo Bay Random Vibration Trunnion Supported Payloads - On P/L Trunnion

Payload Weight *Less Than 10,000 Lbs.		
o All Axes	20 to 60 Hz 60 to 100 Hz 100 to 300 Hz 300 to 2000 Hz Overall = 1.9 g(rms)	.0023 G^2/Hz +9 dB/oct 0.01 G^2/Hz -9 dB/oct
Payload Weight *Greater Than 10,000 Lbs.		
o All Axes	20 to 480 Hz 480 to 2000 Hz Overall = 1.2 g(rms)	.0023 G^2/Hz -9 dB/oct

The associated time duration is 20 seconds per flight which includes a fatigue scatter factor of 4.

*Total payload weight is irrespective of the number of mounting points.

Figure C-20. Orbiter/Cargo Bay Random Vibration Trunnion Supported Payloads - On P/L Keel Pin for payloads weighing less than 10,000 lb and for payloads of greater than 10,000 lb. The longeron trunnion criteria are further defined for two zones of the payload bay: from station X_o = 582 to station X_o = 919 and from station X_o = 919 to station X_o = 1307. The longeron trunnion and keel trunnion criteria corresponds to vibration levels associated with the lift-off event.

C.4.6.2 Random Vibration for Longeron/Adapter Mounted Payloads

The random vibration environments for hardware mounted on the Orbiter payload bay longeron through an adapter is given in Figure C-21. The criteria are defined for two zones of the longeron: from station X_o = 582 to station X_o = 919 and from station X_o = 919 to station X_o = 1307. The criteria corresponds to vibration levels associated with the lift-off event.

Since the design of a mounting is not required at this time, consider the maximum values of Figures C-19, C-20 and C-21.

C.4.6.3 Orbiter-to-Cargo Element Electrical Interface Random Vibration Environment

During launch and ascent, the random vibration environment of STS-to-Cargo Element Electrical Interfaces shall not exceed the following:

20-100 Hz:	+6db/octave
100-1000 Hz:	0.5 g^2/Hz
1000-2000 Hz:	-6db/octave

Duration: 40 Seconds/Flight in 3 Orthogonal Axes

Launch and ascent electrical interfaces will apply to monitoring and safety electrical equipment that operate when the reactor and conversion system are inoperative.

o X Axis	20 to 100 Hz 100 to 500 Hz 500 to 2000 Hz Overall = 5.4 g(rms)	+6 dB/oct .03 G^2/Hz -4 dB/oct
o Y Axis (Fwd of Sta. Xo = 919)	20 to 40 Hz 40 to 100 Hz 100 to 170 Hz 170 to 600 Hz 600 to 2000 Hz Overall = 4.5 g(rms)	+12 dB/oct .06 G^2/Hz -6 dB/oct .02 G^2/Hz -9 dB/oct
o Y Axis (Aft of Sta. Xo = 919)	20 to 40 Hz 40 to 500 Hz 500 to 2000 Hz Overall = 7.8 g(rms)	+12 dB/oct .06 G^2/Hz -4 dB/oct
o Z Axis	20 to 100 Hz 100 to 1000 Hz Overall = 7.6 g(rms)	+6 dB/oct .03 G^2/Hz

The associated time duration is 20 seconds per axis per flight which includes a scatter factor of 4.

Figure C-21. Orbiter/Cargo Bay Random Vibration Longeron/ Adapter Supported Payloads - at Orbiter Interface

C.4.7 Payload Minimum Frequencies/Flight Control Interaction

C.4.7.1 Applicability

The requirements herein are applicable to all flight control regimes (ascent, on-orbit, and descent) with the payloads in their stowed positions and the Cargo Bay doors closed. Acceptability in the on-orbit mode with payloads extended and the doors open is a loads and fuel consumption problem, and is not covered in this section. The acceptability criteria herein is based on the descent mode requirements. If these requirements are met, the system will be acceptable for all flight modes.

C.4.7.2 Single/Multiple Payloads Frequency Requirements

These requirements cover both multiple and single payloads for both nominal and heavy landed payloads. (The latter are in excess of 32,000 lb.) The requirements are based on the lift-off mass and modal characteristics of the payloads and their constraint systems. The criteria consist of a definition of the minimum acceptable constrained frequency as a function of payload weight. Any individual payload that is a portion of the total cargo manifest (a multiple payload cargo) and whose lift-off weight is less than 45,000 lb, shall meet the requirements for a 45,000 lb payload; if in excess of 45,000 lb, the constrained frequency requirements for the heavier weight must be met. Constrained frequency is defined as the frequency of the payload on its mounts, with the mounts fixed to an infinite mass. These frequencies can be attributed either to the inherent flexible characteristics of the payload and/or to the suspension characteristics of the rigid payload.

Nuclear reactor and conversion system equipment designs must meet these requirements for launch, on-orbit and descent so as to avoid damage to the equipment or be hazardous to the shuttle and the crew.

C.4.7.3 Criteria

The minimum acceptable payload constrained frequency is presented in Figure C-22 for damping ratios (δ) from 0.005 to 0.04 (0.05% to 4%). The plot is applicable to the pitch, roll and yaw (rudder/yaw jet) modes. The constrained frequencies are associated with the primary pitch/plunge and lateral payload modes. For damping ratios between the defined values, a linear interpolation is permissible. If δ is greater than 0.04, the 0.04 value must be used.

Damping ratios up to 0.01 can be used for preliminary flight control interaction analysis. Higher damping ratios must be verified per JSC 14046 (Payload Interface Verification Requirements).

As shown, a 32,000 lb single payload with 0.01 damping requires a minimum frequency of 37.5 radians per second. The requirements for a single 45,000 lb payload, or for any lighter weight payload that is part of a 45,000 lb multiple payload cargo, is at least 39.75 radians per second when δ is 0.01.

C.5 <u>Aft Flight Deck</u>

C.5.1 Limit-Load Factors

(See Paragraph C.4.3 for definition of load factor).

C.5.1.1 Operational Inertia Load Factors

Operational inertia load factors shown in Figure C-23 shall apply to all secondary structure.

C.5.2 Emergency Landing Load Factors

The emergency load factors specified below shall apply to components mounted in the crew compartments. They shall not apply to items whose failure does not result in injury to personnel or prevent egress from the crashed vehicle.

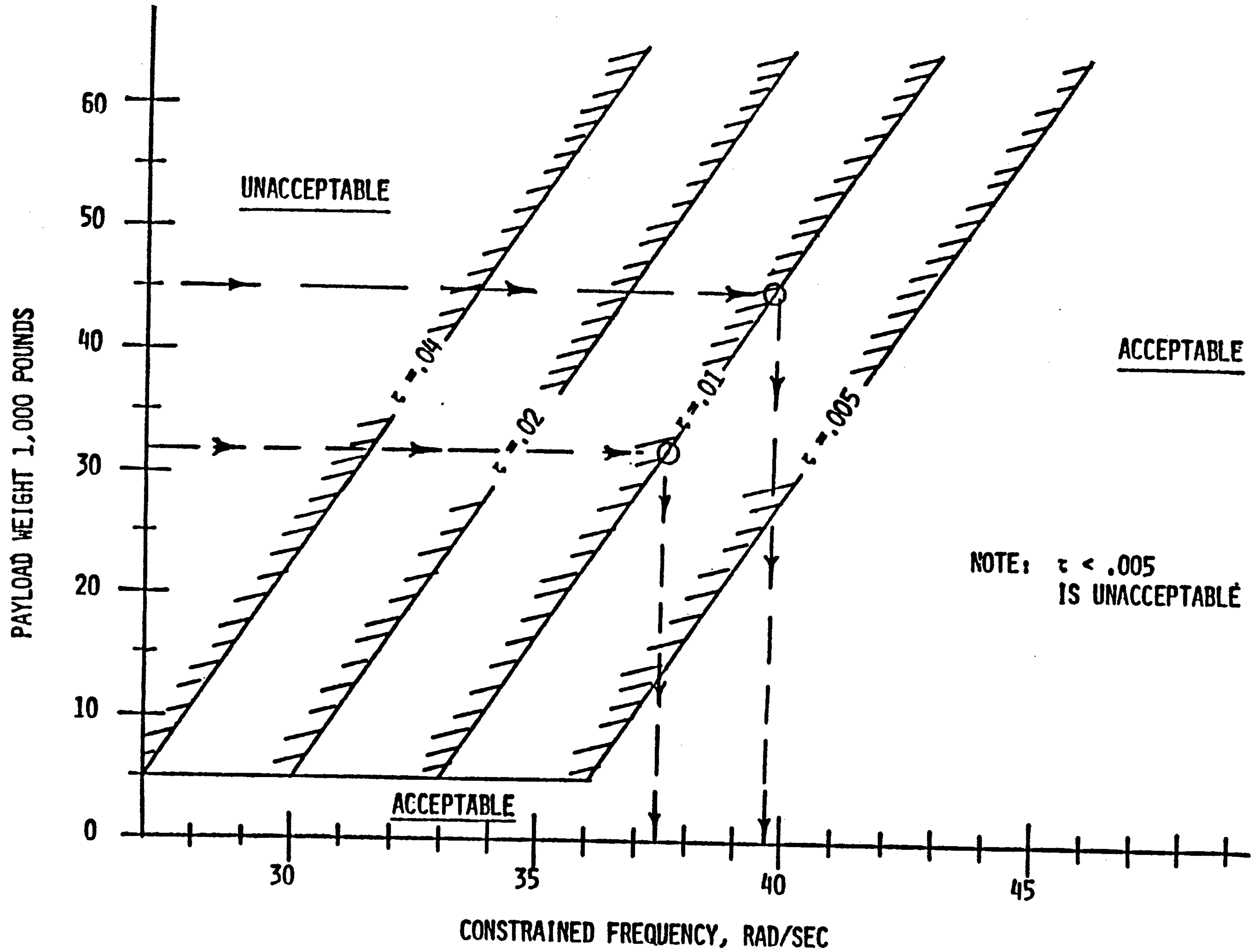


Figure C-22. Minimum Frequency Requirements

Condition	Limit	Load	Factors
	Nx	Ny	Nz
	-2.55	0	.55
Lift-Off	-2.23	-.03	1.68
	-1.28	.01	-2.05
High-q Boost	-1.90	.04	-.20
	-1.60	±.20	-.20
Max Boost	-3.20	.09	-.20
Orbiter Max Load Factor	-3.25	-.02	-.60
	-3.01	0	-.77
TAEM Maneuvers	1.21	0	2.5
	0.53	1.67	1.02
	0.21	-1.39	0.90
Landing	3.57	0	.96
	-2.96	0	.35
	-.60	0	4.9(1)

(1) Nz is 4.9g at the crew module C.G. only. It varies linearly with X from 6.68g at the forward bulkhead to 3.70g at the aft bulkhead.

Figure C-23. Operational Inertia Load Factors

Ultimate Inertia Load Factors		
Nx	Ny	Nz
20.0 -3.3	3.3 -3.3	10.0 -4.4

These load factors shall act independently, and the longitudinal load factors shall be directed within 20° of the longitudinal axis.

C.5.3 Random Vibration

The random vibration environments applicable to components mounted in the Aft Flight Deck during launch and ascent shall be as follows:

20 - 150 Hz	+6.00 dB/Octave
150 - 1000 Hz	0.03 g^2/Hz
1000 - 2000 Hz	-6.00 dB/Octave Composite = 6.5 g (rms)

Environment exposure duration = 7.2 sec/flight in each of X_o, Y_o, and Z_o axes.

The exposure duration of 7.2 seconds/flight does not include a fatigue scatter factor. A fatigue scatter factor appropriate for the materials and method of construction is required and shall be not less than 4.0.

C.5.4 Acoustics

Figure C-24 represents the minimum level to which equipment to be flown in the aft flight deck must be certified to be considered safe to fly on the STS.

1/3 Octave Band Center Frequency (Hz)	Sound Pressure Level - dB ref. 2 x $10^{-5} N/m^2$	
	Lift-Off	Aeronoise
	5 Seconds/Flight*	10 Seconds/Flight*
31.5	107	99
40.0	108	100
50.0	109	100
63.0	109	100
80.0	108	100
100.0	107	100
125.0	106	100
160.0	105	99
200.0	104	99
250.0	103	99
315.0	102	98
400.0	101	98
500.0	100	97
630.0	99	97
800.0	98	96
1000.0	97	95
1250.0	96	94
1600.0	95	93
2000.0	94	92
2500.0	93	91
OVERALL	117.5	111

* Time per flight does not include a scatter factor.

Figure C-24. Aft Flight Deck Acoustic Environment

C.5.5 Panel Kick/Push-Off Loads

In areas where panel deflection could cause equipment damage to payload provided Aft Flight Deck equipment, the panel shall be capable of absorbing a limit of 125 lb (56.7 kg) load distributed over a 4 in. x 4 in. (101.6 mm x 101.6 mm) square area.

C.6 General Accelerations

C.6.1 RCS/VRCS Accelerations

During normal Orbiter attitude-keeping activities, thrusting of the Orbiter RCS will cause slight accelerations to be exerted on cargo elements depending on their locations with respect to the vehicle center of rotation (affected by weight distribution, but generally in the vicinity of $X_0 = 1120$, $Y_0 = 0$, $Z_0 = 400$). RCS acceleration values shall be as defined in Figure C-25. Vernier RCS acceleration values shall be as defined in Figure C-26. In either case, all three angular accelerations may occur simultaneously.

C.6.2 Prelaunch Accelerations

Maximum and minimum limit-load factors/angular accelerations exerted on the cargo during prelaunch shall be as specified in Figures C-27 and C-28 for an unfueled (empty) and fueled (full) Shuttle External Tank (ET), respectively. These data are based upon the dynamic response of the cargo, with the Cargo Bay door closed, in a Shuttle vehicle which is exposed to ground wind loading, including gust and vortex shedding effects. The Rotating Service Structure (RSS) and other Shuttle service connections are retracted. The dynamic response is maximized such that these data may be applied conservatively to cargo elements of all weights at all locations.

Limit-load factor/angular acceleration, including sign convention, is defined in Paragraph C4.3. The center of rotation for angular accelerations is at the cargo element center of gravity. A zero degree wind vector coincides with the

Acceleration	Command	Maximum Hi-Mode	Nominal Mode	Time Average
TRANSLATION (ft/sec²)				
32 K lbs Payload	+X	0.55*	0.27	0.29
	-X	N/A	-0.28	-0.27
	+Y	N/A	0.28	0.12
	-Y	N/A	-0.28	-0.15
	+Z	1.26**	0.42	0.43
	-Z	-0.94*	-0.55	-0.50
65 K lbs Payload	+X	0.46*	0.23	0.24
	-X	N/A	-0.23	-0.22
	+Y	N/A	0.23	0.10
	-Y	N/A	-0.23	-0.12
	+Z	1.05**	0.35	0.35
	-Z	-0.80	-0.46	-0.42
ROTATION (deg/sec²)				
32 K lbs Payload	+Roll	N/A	1.09	0.80
	-Roll	N/A	-1.09	-0.89
	+Pitch	N/A	1.29	1.16
	-Pitch	N/A	-0.86	-0.81
	+Yaw	N/A	0.72	0.70
	-Yaw	N/A	-0.72	-0.62
65 K lbs Payload	+Roll	N/A	1.03	0.76
	-Roll	N/A	-1.03	-0.84
	+Pitch	N/A	1.18	1.06
	-Pitch	N/A	-0.79	-0.74
	+Yaw	N/A	0.66	0.64
	-Yaw	N/A	-0.66	-0.57

* Hi-mode acceleration in +X and -Z is available only during OPS 1 (insertion) and OPS 3 (de-orbit) phases with TRANS DAP (Transition, digital autopilot).

** Hi-mode acceleration in +Z is available only during OPS 2 (on-orbit) phase with on-orbit DAP (digital autopilot).

Figure C-25. Orbiter Per Axis Primary RCS/VRCS Acceleration Levels

Payload	Rotation Command	Per Axis Rotational Acceleration deg/sec²	Translational Crosscouple Acceleration, feet/second² X	Y	Z
32 K Lbs	+Pitch	0.0209	-0.0003	0.0	-0.0056
	-Pitch	-0.0163	0.0	0.0	-0.0077
	+Roll	0.0209	-0.0001	0.0027	-0.0067
	-Roll	-0.0209	-0.0001	-0.0027	-0.0067
	+Yaw	0.0175	-0.0001	-0.0011	-0.0029
	-Yaw	-0.0175	-0.0001	-0.0011	-0.0029
65 K Lbs	+Pitch	0.0191	-0.0002	0.0	-0.0047
	-Pitch	-0.0149	0.0	0.0	-0.0064
	+Roll	0.0196	-0.0001	0.0023	-0.0056
	-Roll	-0.0196	-0.0001	-0.0023	-0.0056
	+Yaw	0.0160	-0.0001	-0.0009	-0.0024
	-Yaw	-0.0160	-0.0001	-0.0009	-0.0024

Figure C-26. Orbiter Per Axis Vernier VRCS Acceleration Levels

Ground Wind speed and Direction	Load Factor			Angular Acceleration Rad/Sec²		
	Ny	Nz	Nx	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$
72 Knots 0°	-1±0.10	±0.05	±0.15	±0.01	±0.10	±0.01
72 Knots 90°	-1±0.05	±0.10	±0.05	±0.06	±0.02	±0.06
72 Knots 180°	-1±0.10	±0.05	±0.15	±0.02	±0.10	±0.02

Figure C-27. Maximum and Minimum Cargo Limit Factors/Angular Accelerations - Prelaunch, External Tank Unfueled (Empty)

Ground Wind speed and Direction	Load Factor			Angular Acceleration Rad/Sec^2		
	Ny	Nz	Nx	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$
49 Knots 0°	-1±0.05	±0.03	±0.08	±0.01	±0.05	±0.01
49 Knots 90°	-1±0.03	±0.05	±0.03	±0.03	±0.01	±0.03
49 Knots 180°	-1±0.05	±0.03	±0.08	±0.01	±0.05	±0.01

Figure C-28. Maximum and Minimum Cargo Limit Factors/Angular Accelerations - Prelaunch, External Tank Fueled (Full)

Orbiter +Z axis. The wind vector rotates clockwise; therefore, 90° wind is from Orbiter +Y to Orbiter -Y.

Prelaunch deflections are defined in ICD 2-0A002, SHUTTLE SYSTEM/LAUNCH PAD AND MIP.

C.6.3 OMS Accelerations

The maximum limit-load factors/angular accelerations exerted on the cargo during OMS engine operation shall be as specified in Figure C-29. The maximum values include the effects of OMS engine thrust overshoot, misalignment, and the dynamic magnification of the payload and Orbiter structures. Limit-load factor/angular acceleration, including sign convention, is defined in Paragraph C.4.3. The center of rotation for angular accelerations is at X_0 1094.9, Y_0 0, Z_0 372 for a 32,000 lb cargo element and at X_0 1093.7, Y_0 0, Z_0 375.9 for a 65,000 lb cargo element.

C.6.4 Orbiter Rollout after Landing and Towing Loads

The Orbiter shall not impose total acceleration levels in Cargo elements which exceed $\pm$ 0.8 g laterally, 1 $\pm$ 1.3 g vertically, and 1 g axially. (Applicable to KSC only).

C.6.5 Payload Deployment Operations

During non-RMS deployment operations, the payload will be capable of sustaining loads imposed by the Shuttle as a result of RCS attitude control. The definition of the flight control system for RCS attitude control will be contained within the appropriate PIP or ICD. OMS and RCS translation will not be considered during payload deployment operations involving erection and/or extension. This requirement does not apply to payloads requiring the RMS for payload deployment/handling operations.

Cargo Weight	Load Factor			Angular Acceleration Rad/Sec^2		
	N_x	N_y	N_z	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$
Up to 32 KLB	-.273	±.0048	-.089	±.0104	±.0051	±.0045
32K to 65 KLB	-.237	±.0042	-.074	±.0096	±.0048	±.0043

Figure C-29. Maximum Cargo Limit-Load Factor/Angular Accelerations for CMS Operation

C.7 Thermal Balance

C.7.1 Shuttle Cargo Bay Temperatures

To analyze the effect of the temperatures in the shuttle bay during launch and return to Earth (during an abort or to return a spent reactor) the following figures show data necessary.

- Figure C-30: Orbiter Surfaces Affecting Cargo Element Thermal Balance
- Figure C-31: Air Temperature Entering the Cargo Bay During Entry - Max. Air Temperature Case
- Figure C-32: Cargo Bay Wall Temperature

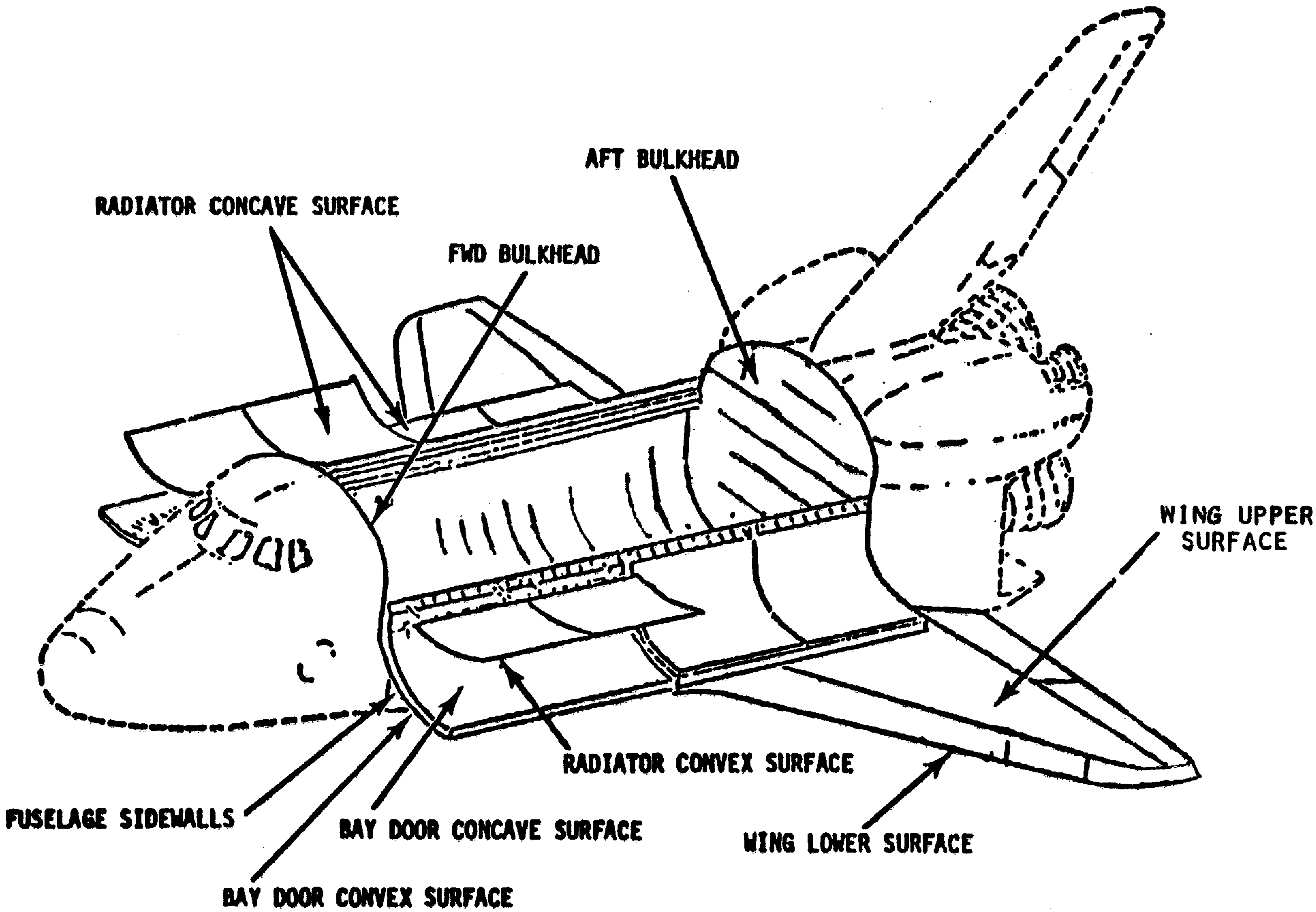


Figure C-30. Orbiter Surfaces Affecting Cargo Element Thermal Balance

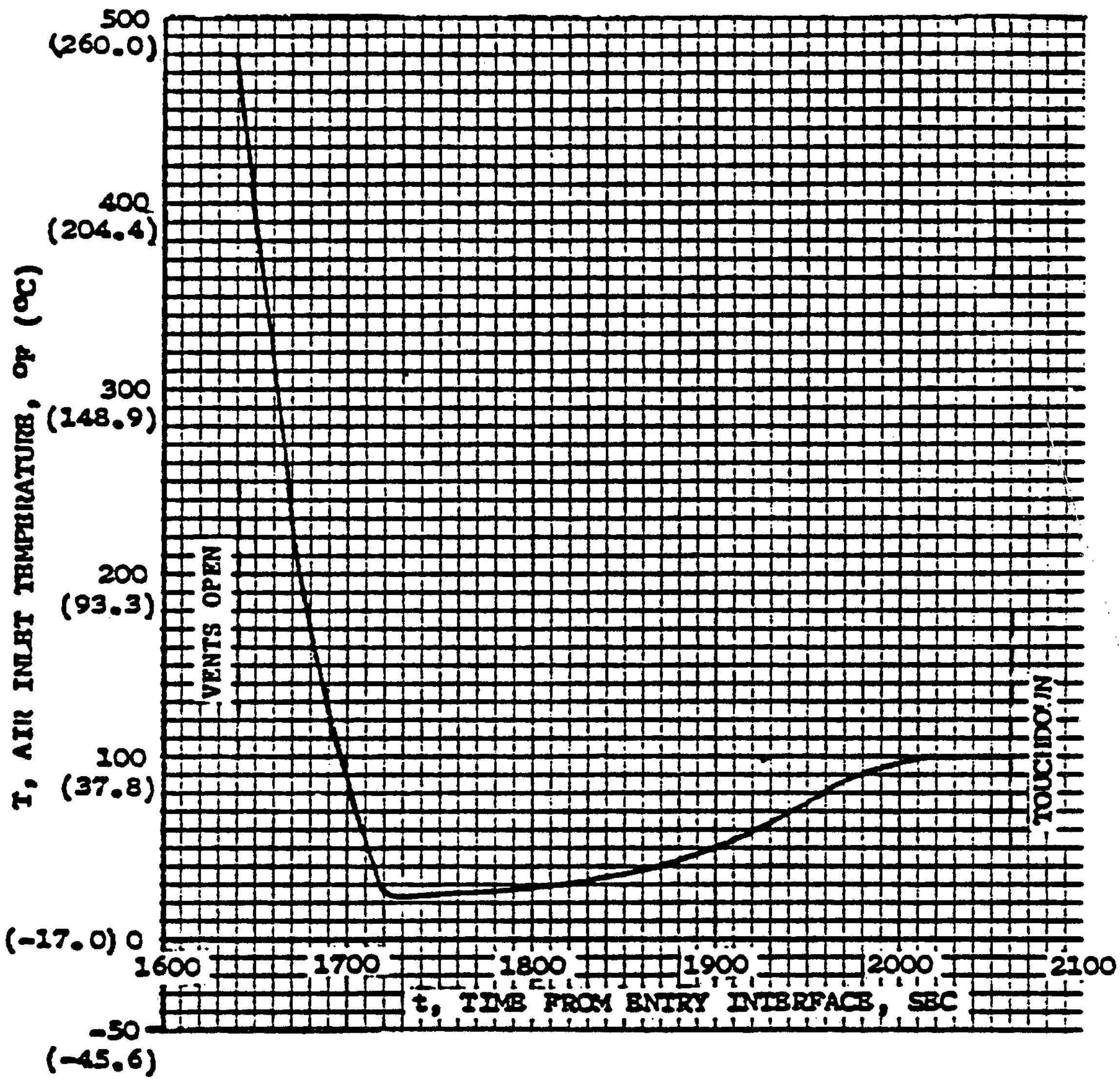


Figure C-31. Air Temperature Entering the Cargo Bay During Entry - Max. Air Temperature Case

Condition	Temperature	
	Minimum	Maximum
1. Prelaunch	+40°F	+120°F
2. Launch	+40°F	+150°F
3. On-Orbit (doors open)	-250°F	+200°F
4. Entry and Post-landing	-50°F	+220°F

__Note__:

a. Conditions 1 and 2 are for an assumed adiabatic cargo element.

b. Condition 3 is for an assumed empty cargo bay. The effect on wall temperature which results with a cargo element installed is dependent upon cargo element configuration, cargo element location in the bay, and on-orbit attitude. Under hot case conditions, cargo element effects can cause local insulation surface wall temperatures to exceed 200°F substantially.

c. Condition 4, minimum, is for an assumed adiabatic cargo element with an initial -250°F cargo bay wall temperature. Condition 4, maximum, is for an assumed empty cargo bay.

d. Conditions 3 and 4 should be analyzed using detailed integrated Orbiter/cargo element math models to define cargo element and Orbiter cargo bay temperatures for specific cargo element configurations.

Figure C-32. Cargo Bay Wall Temperature

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15. ABSTRACT--PURPOSE, SCOPE, APPROACH, RESULTS, CONCLUSIONS, SIGNIFICANCE: (MAXIMUM: 200 WORDS)

This Topical Report presents the results of Task 1 of the Feasibility Assessment for Space-Based Multimegawatt MHD Power Systems program and consists of two volumes. Volume I contains the System Design, Key Technical Issues, R&D Plan and Recommendations. Volume II contains the System Requirements, Design Guidelines and Assumptions for the MHD power system. Supplemental information, including cost estimates, is in WAESD-TR-88-0004.

16. THIS WAESD-TN SHOULD BE DESTROYED AFTER N/A MONTH N/A YEAR.

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